

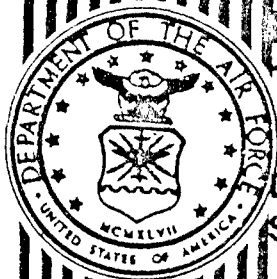
# LOAN DOCUMENT

20030226118

<p style="font-size: 2em; margin: 0;">AD-A261 179</p>	DTIC ACCESSION NUMBER	<div style="border: 1px solid black; width: 100px; height: 50px; margin: 0 auto;"></div> <p style="margin: 0;">LEVEL</p>	<p style="margin: 0;">PHOTOGRAPH THIS SHEET</p>	<div style="border: 1px solid black; width: 100px; height: 50px; margin: 0 auto; display: flex; align-items: center; justify-content: center;"> <span style="font-size: 3em;">①</span> </div> <p style="margin: 0;">INVENTORY</p>																										
	<p style="font-size: 1.5em; margin: 0;">ESL-TR-90-21 Vol. 3</p> <p style="margin: 0;">DOCUMENT IDENTIFICATION</p> <p style="margin: 0;">Aug 91</p>																													
	<div style="border: 1px solid black; padding: 10px; margin: 0 auto; width: 80%;"> <p style="margin: 0;"><del>DISTRIBUTION STATEMENT F</del></p> <p style="margin: 0;">Approved for public release</p> <p style="margin: 0;">Distribution Unlimited</p> </div>																													
<p style="margin: 0;">DISTRIBUTION STATEMENT</p>																														
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td colspan="2" style="text-align: center; font-size: 0.8em;">ACCESSION FOR</td> </tr> <tr> <td style="width: 50%; font-size: 0.7em;">NTIS</td> <td style="width: 50%; font-size: 0.7em;">GRAM</td> </tr> <tr> <td style="font-size: 0.7em;">DTIC</td> <td style="font-size: 0.7em;">TRAC</td> </tr> <tr> <td style="font-size: 0.7em;">UNANNOUNCED</td> <td style="font-size: 0.7em;">JUSTIFICATION</td> </tr> <tr> <td colspan="2" style="height: 20px;"></td> </tr> <tr> <td colspan="2" style="height: 20px;"></td> </tr> <tr> <td colspan="2" style="height: 20px;"></td> </tr> <tr> <td colspan="2" style="height: 20px;"></td> </tr> <tr> <td colspan="2" style="font-size: 0.8em;">BY</td> </tr> <tr> <td colspan="2" style="font-size: 0.8em;">DISTRIBUTION/</td> </tr> <tr> <td colspan="2" style="font-size: 0.8em;">AVAILABILITY CODES</td> </tr> <tr> <td style="font-size: 0.7em;">DISTRIBUTION</td> <td style="font-size: 0.7em;">AVAILABILITY AND/OR SPECIAL</td> </tr> <tr> <td style="height: 40px; vertical-align: middle; font-size: 2em;">A-1</td> <td></td> </tr> </table>		ACCESSION FOR		NTIS	GRAM	DTIC	TRAC	UNANNOUNCED	JUSTIFICATION									BY		DISTRIBUTION/		AVAILABILITY CODES		DISTRIBUTION	AVAILABILITY AND/OR SPECIAL	A-1		<div style="border: 1px solid black; padding: 10px; margin: 0 auto; width: 80%;"> <p style="font-size: 2em; margin: 0;">DTIC</p> <p style="font-size: 1.5em; margin: 0;">ELECTE</p> <p style="font-size: 1.2em; margin: 0;">JAN 29 1993</p> <p style="font-size: 2em; margin: 0;">S C D</p> </div>		
ACCESSION FOR																														
NTIS	GRAM																													
DTIC	TRAC																													
UNANNOUNCED	JUSTIFICATION																													
BY																														
DISTRIBUTION/																														
AVAILABILITY CODES																														
DISTRIBUTION	AVAILABILITY AND/OR SPECIAL																													
A-1																														
<p style="margin: 0;">DISTRIBUTION STAMP</p>		<p style="margin: 0;">DATE ACCESSIONED</p>																												
		<p style="margin: 0;">DATE RETURNED</p>																												
<p style="margin: 0;">DATE RECEIVED IN DTIC</p>		<p style="font-size: 1.5em; margin: 0;">93-01525</p> <p style="margin: 0;">yes 32106</p>																												
<p style="margin: 0;">PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-FDAC</p>																														

HANDLE WITH CARE

ESL-TR-90-21  
VOL III



# **IN SITU SOIL VENTING - FULL SCALE TEST HILL AFB**

**D. W. DEPAOLI, S. E. HERBES, J. H. WILSON, D. K.  
SOLOMON, AND H. L. JENNINGS**

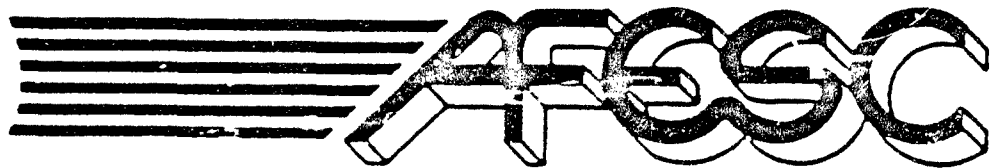
**MARTIN-MARIETTA ENERGY SYSTEMS  
OAK RIDGE NATIONAL LABORATORY  
P. O. BOX 2008  
OAK RIDGE TN 37831**

**AUGUST 1991**

**FINAL REPORT**

**OCTOBER 1987 - JANUARY 1990**

**APPROVED FOR PUBLIC RELEASE. DISTRIBUTION  
UNLIMITED.**



**AIR FORCE ENGINEERING & SERVICES CENTER  
ENGINEERING & SERVICES LABORATORY  
TYNDALL AIR FORCE BASE, FLORIDA 32403**

00 1 10 187

NOTICE

PLEASE DO NOT REQUEST COPIES OF THIS REPORT FROM  
HQ AFESC/RD (ENGINEERING AND SERVICES LABORATORY).  
ADDITIONAL COPIES MAY BE PURCHASED FROM:

NATIONAL TECHNICAL INFORMATION SERVICE  
5285 PORT ROYAL ROAD  
SPRINGFIELD, VIRGINIA 22161

FEDERAL GOVERNMENT AGENCIES AND THEIR CONTRACTORS  
REGISTERED WITH DEFENSE TECHNICAL INFORMATION CENTER  
SHOULD DIRECT REQUESTS FOR COPIES OF THIS REPORT TO:

DEFENSE TECHNICAL INFORMATION CENTER  
CAMERON STATION  
ALEXANDRIA, VIRGINIA 22314

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved CMB No 0704 014b	
1a REPORT SECURITY CLASSIFICATION			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION AVAILABILITY OF REPORT Approved for Public Release Distribution Unlimited		
2b DECLASSIFICATION/DOWNGRADING SCHEDULE					
4 PERFORMING ORGANIZATION REPORT NUMBER(S) Final Report DOE Project No. 1489-1489-A1			5 MONITORING ORGANIZATION REPORT NUMBER(S) ESL-TR-90-21		
6a NAME OF PERFORMING ORGANIZATION Martin-Marietta Energy Systems Oak Ridge National Laboratory		6b OFFICE SYMBOL (if applicable)	7a NAME OF MONITORING ORGANIZATION Air Force Engineering & Services Center		
6c ADDRESS (City, State, and ZIP Code) P. O. Box 2008 Oak Ridge TN 37831			7b ADDRESS (City, State, and ZIP Code) HQ AFESC/RDVW Tyndall AFB FL 32403-6001		
8a NAME OF FUNDING SPONSORING ORGANIZATION Engineering & Services Center		8b OFFICE SYMBOL (if applicable) RDV	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER IAC Project 1489-1489-A1		
8c ADDRESS (City, State, and ZIP Code) Air Force Engineering & Services Center Tyndall AFB FL 32403-6001			10 SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO 63723F	PROJECT NO. 2103	TASK NO 70
					WORK UNIT ACCESSION NO 98
11 TITLE (Include Security Classification) (U) In Situ Soil Venting - Full Scale Test Hill AFB, Guidance Document, Literature Review					
12 PERSONAL AUTHOR(S) D. W. DePao; L. S. E. Herbes; J. H. Wilson; D. K. Solomon; Jennings, H. L.					
13a TYPE OF REPORT Final		13b TIME COVERED FROM 8710 TO 9001		14 DATE OF REPORT (Year, Month, Day) August 1991	
15 SUPPLEMENTARY NOTATION Availability of this report is specified on reverse of the front cover					
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			
06	13		Soil Venting Fuel Spill Remediation Bioremediation Vacuum Extraction		
19 ABSTRACT (Continue on reverse if necessary and identify by block number) The purpose of this project was to demonstrate a full-scale in situ soil venting technology and to carefully document the design, operation and performance of this system so that it could be applied at other Air Force contaminated sites. Although this technology is now commercially available, its ability to fully remediate jet fuel spills had never been proven, nor had the full-scale costs ever been validated when catalytic incineration is used as an emission control method. ESL Technical Report 90-21 is in three volumes. The first volume is a complete literature review of previous soil venting research and field work. Volume II is a guidance manual which provides important design information and describes methods of pilot testing this technology prior to full-scale application. Results of the Hill AFB test are included in Volume III. These publications will provide invaluable information to Air Force engineers responsible for cleaning up chemically contaminated sites.					
20 DISTRIBUTION AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a NAME OF RESPONSIBLE INDIVIDUAL Douglas C. Downey			22b TELEPHONE (Include Area Code) (904) 283-2942		22c OFFICE SYMBOL RDVW



## EXECUTIVE SUMMARY

### A. OBJECTIVES

Oak Ridge National Laboratory (ORNL) was contracted by the Air Force Engineering and Services Center (AFESC) to field test the feasibility of using *in situ* soil venting to remove organic contaminants from unsaturated soils. The objectives of this demonstration project were to determine the cleanup efficiencies attainable using *in situ* soil venting for remediation of fuel-contaminated sites and to define operating, cost, and system design parameters for application of soil venting at other Air Force sites. The data collected were to be used in the study of factors controlling venting effectiveness.

### B. BACKGROUND

Over 4,000 Air Force sites are known or suspected to have contaminated groundwater and soil. The most common contaminants are fuels and chlorinated solvents. Since many of these contaminants are volatile or have volatile components, a relatively inexpensive and effective method for the cleanup of these sites is *in situ* soil venting, also referred to as *in situ* air stripping, soil vapor extraction, and vacuum extraction. In this technique, large volumes of air are passed through contaminated soil zones. This results in volatilization of the contaminants and subsequent removal in the gas stream.

The site selected for the *in situ* soil venting demonstration was a fuel storage area at Hill AFB, Utah, where 27,000 gallons (102,000 liters) of JP-4 were spilled by the overfilling of an underground storage tank in January 1985. This site was selected because of several favorable characteristics, including nearly ideal geohydrology, significant JP-4 contamination in the soil, logistical support, and the opportunity to undertake tests of different venting configurations.

### C. SCOPE

This report is part of a technical effort comprised of three main tasks: (1) review of the literature and assessment of the technology, (2) preparation of a guidance manual for application of soil venting at other Air Force sites, and (3) demonstration and analysis of full-scale venting. The results of the first two tasks are presented in AFESC ESL TR 90-21 Vol. I and ESL TR 90-21 Vol. II, respectively. The scope of the full-scale demonstration activities described in this report include site selection, site characterization, pilot studies, full-scale system design and construction, test operation, and post-operation site characterization.

### D. METHODOLOGY

Site characterization activities included testing to determine both soil properties and contaminant distribution. Stratigraphy and soil types were determined by continuous logging and sampling of 64 boreholes. Soil moisture was determined by analysis of intact cores and by *in situ* measurement utilizing neutron absorption. Bulk density and porosity measurements were made on core samples. Contaminant areal distribution was determined by soil gas analysis. Three-dimensional contaminant distribution, both in terms of total hydrocarbon concentration and hydrocarbon composition, was measured by extraction and gas chromatographic analysis of intact soil core samples.

Pilot studies were used to determine site-specific parameters needed in the design of the full-scale system. Tests conducted included limited bench testing, development and application of an *in situ* air permeability procedure, a single vent pilot test, and flow modelling for the purpose of determining vent spacings.

The full-scale system was designed and operated to provide information regarding factors controlling hydrocarbon removal by volatilization and by biodegradation. Throughout the operations, the hydrocarbon concentration and composition and oxygen and carbon dioxide levels in the extracted gas were measured, as well as temperatures and pressures throughout the system and extraction and inlet gas flow rates.

## E. TEST DESCRIPTION

The full-scale venting system consisted of three subsystems: (1) an array of 15 vertical vents and 31 pressure monitoring wells in the area west of the spill source, (2) a set of six lateral vents and 30 pressure monitoring probes installed under a new concrete pad and dike constructed for the tanks after the spill, and (3) a set of lateral vents in the pile of soil retained after excavation of the tanks. This design included features that permitted evaluation of several factors affecting contaminant transport and subsurface airflow.

A common blower/emissions control system was installed for inducing airflow from the three vent arrays and for treating emissions as necessary to meet regulatory requirements of the state of Utah. Two rotary-lobe blowers provided the capability for extraction of up to 1500 standard cubic feet per minute (scfm) [43 standard cubic meters per minute (scmm)] of gas from the three vent systems at vacuum levels up to approximately 100 inches of water (25,000 Pascals). In order to protect against potential hazards presented by combustible gas mixtures, flame arrestors were installed at the inlet to each blower. The blowers were controlled by an automatic shutdown system based on the output from a combustible gas detector. Two catalytic oxidation units were used for conversion of the jet fuel hydrocarbons to carbon dioxide and water before discharge into the atmosphere. The propane-fired units differed in the configuration of their catalyst beds; one had a fluidized-bed design and the other a fixed-bed design. The units were evaluated in terms of economics and reliability, as well as hydrocarbon destruction efficiency. A vapor/liquid separator, flowmeters, and gas monitors were also included in the system.

Operation of the system fell into five distinct modes: (1) the initial period of manned operation during which dilution of the high concentration soil gas was necessary, (2) three shutdown periods of one to three weeks for the monitoring of subsurface biological activity, (3) operation of different vent configurations for the measurement of pressure and flow fields induced by different venting strategies, (4) long-term unmanned system operation, and (5) a period of operation including injection of hot exhaust gas from the catalytic oxidation units for evaluation of removal enhancement by heating.

## F. RESULTS

Site characterization before system operation indicated that the soil generally consisted of unconsolidated to weakly consolidated sand, with thin lenses of clay. Air permeability measurements ranged from  $3 \times 10^{-12}$  to  $6 \times 10^{-11}$  square meters ( $m^2$ ). Moisture content was generally 3 to 7 weight percent, with higher values (10 to 25 weight percent) associated with clay lenses. Moisture levels

remained essentially unchanged throughout the demonstration period. The hydrocarbon contamination was limited to a soil zone of approximately 120 ft x 120 ft x 50 ft (37 meters x 37 meters x 15 meters deep). Total hydrocarbon soil concentration measurements ranged from below detection [20 milligrams/kilogram (mg/kg)] to 6400 mg/kg. A calculation of total hydrocarbon mass present in the soil prior to venting yielded an estimate of 39,300 pounds (17,800 kg).

The ORNL operation of the Hill AFB full-scale *in situ* soil venting system began in December 1988. Between 16 December 1988 and 9 October 1989, a total of 105,000 pounds (47,600 kg) of hydrocarbons was extracted in 167 million standard cubic feet (scf) (4.8 million standard cubic meters) of soil gas. During this period the extracted soil gas concentrations decreased from an initial level of approximately 45,000 parts-per-million-by-volume (ppmv) hexane equivalent to a final concentration of 350 ppmv. The final average concentration of the gas from the vertical vents alone was 157 ppmv.

The behavior of the hydrocarbon concentration as measured in the extracted gas, and thus the removal rate, was characteristic of soil venting operations, with a rapid decrease in concentration from initially high hydrocarbon levels, followed by an extended period with a much more slowly decreasing removal rate. The composition of the hydrocarbons in the extracted gas shifted from lighter, more volatile compounds to heavier, less volatile compounds in concert with the concentration decrease. An equilibrium model based on Raoult's Law was found to be in good agreement with the hydrocarbon concentration and composition results, indicating that mass transfer limitations were insignificant during most of the venting period.

A potentially significant means of hydrocarbon removal due to *in situ* soil venting is enhanced biodegradation. The increased oxygen levels in the soil gas due to infiltration of atmospheric air may stimulate biological activity. Results of carbon dioxide and oxygen measurements of the extracted gas indicated that initially high carbon dioxide and low oxygen levels in the soil were altered by venting. Although carbon dioxide levels decreased and oxygen levels increased during operation, carbon dioxide levels remained an order of magnitude higher than background, indicating that significant biodegradation was occurring. Other tests, including microbial characterization, isotopic analyses, bench studies, and measurements of oxygen uptake and carbon dioxide generation during shutdown tests were conducted by Batelle-Columbus Laboratories and provided further evidence of hydrocarbon biodegradation. Integration of the difference between extracted soil gas and atmospheric carbon dioxide and oxygen levels indicated that bioactivity contributed about 15 percent of the total hydrocarbon removal during the first four months of the demonstration. An estimated total of 16,000 pounds (7300 kg) of hydrocarbons were converted by biodegradation over the course of the demonstration.

Catalytic oxidation was demonstrated to be an attractive means of emissions control for soil venting systems. Both units tested yielded adequate hydrocarbon destruction when operated at appropriate conditions. Also, both units provided nearly trouble-free, unmanned operation. The units differed somewhat in economics of operation, the fixed-bed design being less expensive due to lower temperatures required for adequate conversion.

The heat injection test involved extraction of a total flow rate of 650 scfm [0.31 cubic meters per second ( $\text{m}^3/\text{second}$ )] from two vents placed on opposite sides of a heated air inlet vent each at a distance of 6.1 meters. The inlet gas was at a temperature of 200-212° F (93-100° C) and a flow rate of about 93 scfm (0.044  $\text{m}^3/\text{second}$ ). After seven weeks of operation, measured temperature increases

ranged from 25°F (13.9°C) at a distance of 1.5 meters from the injection vent to 5°F (2.8°C) in the extracted gas. An increase in the extracted gas hydrocarbon concentration qualitatively corresponded with the arrival of the soil temperature front at the extraction vents. Hydrocarbon removal from the system as a whole during the test period was increased by about 9 percent due to heating, while removal was enhanced by 60 percent within the heated zone. Limited economic projections indicate that the strategy may be advantageous provided that heat can be more evenly distributed throughout contaminated soil zones.

Post-operation soil sampling resulted in measurements of total hydrocarbon concentrations ranging from nondetectable (less than 20 mg/kg) to a maximum of 424 mg/kg. Only 9 analyses out of 124 exceeded 100 mg/kg, the action level in several states. Hydrocarbon removal performance as calculated by comparison of pre- and post-operation characterization was 94.8 percent for the vertical vent system and 95.5 percent for the pile. The zone beneath the tanks was not sampled after operation. The paired pre- and post-operation soil samples showed no effect of clay or moisture content on removal at this site. Shallower soil zones were treated as well or better than deeper soil zones, and soil zones with higher gas flows exhibited greater hydrocarbon removal. Soil gas levels, as measured by extraction of equilibrated soil gas from each vent, corresponded reasonably well with soil concentration and provided a sensitive, rapid, and inexpensive method of determining relative areal contamination and the extent of cleanup.

## G. CONCLUSIONS

This study demonstrated that *in situ* soil venting is an effective technique for the remediation of jet fuel spill sites in sandy soils. The experience gained during this test has provided additional information and insight into the applicability and factors controlling soil venting systems. Several major points are discussed in the following paragraphs.

Pilot testing proved extremely valuable for implementation of the full-scale system. *In situ* permeability tests proved to be a useful method for quick and inexpensive, but accurate, determination of air permeability at various points in the soil. A single-vent pilot test allowed measurement of expected extracted gas hydrocarbon concentrations as well as site data regarding the effect of soil conditions upon vacuum requirements and flow distribution. Future pilot tests should be operated for longer periods and include a shutdown, equilibration, and restart for determination of the importance of diffusion upon removal under the site conditions. Bench-scale testing did not prove to be a useful extrapolation technique for prediction of full-scale remediation; however, bench-scale tests are urged for determination of empirical site-specific relations between soil contaminant concentration and equilibrated gas concentration.

This demonstration showed soil venting to be very effective for JP-4 hydrocarbon removal. During the 9 months of operation, volatilization removed 105,000 pounds (47,600 kg), and another 16,000 pounds (7300 kg) were converted by biodegradation. This corresponds to 69 percent removal of the initial spill mass, of which an unknown value remained at the commencement of operation. Because a significant but unmeasured portion of the spilled fuel immediately ran off the site into a downgradient ditch, the actual removal efficiency was undoubtedly considerably higher. Total hydrocarbon levels in the soil were reduced by 95 percent, and a corresponding drop of 99 percent was noted in soil gas levels. Only 7 percent of the post-operation soil samples exhibited total hydrocarbon levels greater than the 100 mg/kg limit used by several states.

Hydrocarbon removal rates from the full-scale Hill AFB system were found to be reasonably well-predicted using a simple, single equilibrium stage Raoult's Law model. Equilibrium models indicate that the 10 weight percent to 20 weight percent of JP-4 representing the least volatile fractions will require a much greater length of time to be removed by volatilization than would be reasonably expected for a site remediation. Therefore, an alternative means may be required if removal of these compounds is necessary to meet regulations.

Biodegradation enhanced by soil aeration caused by *in situ* soil venting may provide the means of removal of the heaviest portion of JP-4, allowing the effective application of the soil venting technology to this hydrocarbon mixture. This demonstration has provided conclusive evidence that aerobic biodegradation of the hydrocarbons in the soil was occurring at significant rates. Biodegradation proceeded at a rate of about 18 percent of the volatilization rate with no effort made toward optimization of the process, by such means as reducing extraction rates, injection of nutrients, or moisture addition.

Based upon a hypothetical regulatory closure criterion of 100 mg/kg of hydrocarbons remaining in the soil (i. e., the limit set for several states), the vertical vented site and soil pile probably would have met regulatory requirements for closure at the end of this demonstration. The post-venting soil sampling was not designed for regulatory purposes (samples were collected in a regular pattern rather than randomly); however, the mean of the analyzed residual hydrocarbon concentrations of 50 mg/kg [Standard Error (SE) 7 mg/kg] would meet the EPA's published criterion for comparison with an action level.

The total quantity of hydrocarbons measured in the vented air stream (47,600 kg), and the quantity measured by difference between pre- and post-venting soil samples (17,750 kg), differ by a factor of nearly 2.7. This difference is probably largely due to withdrawal of fuel vapors from a zone larger than the zone defined by the soil samples which were collected from boreholes. The magnitude of difference between these two numbers, in a system which was relatively uniform geologically and from which several hundred soil samples were analyzed, suggests that in most cases it will be unrealistic to expect that pre-venting soil analyses will yield an accurate measure of extractable hydrocarbons.

An estimate of the range of remediation cost for the Hill AFB site was made using an equilibrium removal model, assuming initial mass equal to the total initial spill amount. Volatilization of 80 percent of the initial spill was specified, with an estimated additional 15 percent destruction by biodegradation, which would result in an averaged soil concentration of less than 100 mg/kg total hydrocarbons. For this case, a range of 1 to 2.6 years of operation would be required, at a total estimated cost of \$741,000 to \$1,019,000. These costs translate to \$4.2 to \$5.8 per pound (\$9.3 to \$12.8/kg) of hydrocarbon removed, or approximately \$28 to \$38 per cubic yard (yd<sup>3</sup>) [\$36 to \$49 per cubic meter (m<sup>3</sup>)] of soil treated. The results of post-venting soil sampling suggest that the Hill AFB remediation would fall on the lower portion of the cost range. The application of these cost numbers to other sites would not be possible without suitable information regarding the air permeability of the soil, total spill volume, and contaminant characteristics. Nevertheless, *in situ* soil venting may be seen as a prospect for effective and economical means of remediation of JP-4 jet fuel at most Air Force sites.

## H. RECOMMENDATIONS

*In situ* soil venting may be considered for remediation of JP-4 jet fuel or other more volatile contaminant spill sites. The technology is likely to be more successful in meeting regulatory requirements if closure limits are based on soil total hydrocarbon concentration or upon soil gas total hydrocarbon concentrations rather than concentrations of individual components.

Pilot testing should be conducted at a potential soil venting site prior to system design for measurement of air permeability and expected extracted gas contaminant concentration.

Future studies should be made in investigation of optimization of bioactivity during soil venting. Further field testing should also be conducted including enhancement of volatilization by heating.

Field testing should continue for investigation of JP-4 and other contaminant removal in less optimal removal cases, such as less permeable soils, moister soils, or a free product layer on groundwater. Field tests must be conducted for extended periods to prove feasibility of site cleanup as well as high removal capabilities.

Bench testing should continue to determine the importance of various factors such as moisture, soil organic content, contaminant type, and diffusion, upon removal mechanism. Such testing would be necessary in the formulation of realistic removal models.

## PREFACE

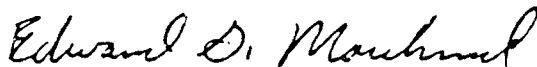
This document was prepared by the Oak Ridge National Laboratory (ORNL), P. O. Box 2008, Oak Ridge, TN 37831-6044, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, FL 32403-6001, as a partial means of fulfillment of the statement of work entitled "In Situ Soil Venting" in accordance with DOE Interagency Agreement No. 1489-1489 A1. ORNL is managed by Martin Marietta Energy Systems, Inc., for the U. S. Department of Energy under contract DE-AC05-84OR214000.

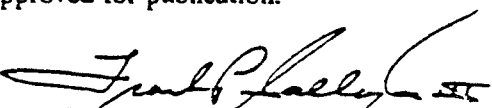
This document details activities performed during the period April 1987 through January 1990 under Task 4.2 of the statement of work, Field Test I. Related documents are ESL TR 90-21 Volume I, In Situ Soil Venting: A Review of the Literature, and ESL TR 90-21 Volume II, Guidance Manual for the Application of In Situ Soil Venting for the Remediation of Soils Contaminated with Volatile Organic Compounds. The AFESC/RDVW Project Officers for this effort were Capt. Edward Heyse, Capt. Michael Elliott, Mr. Doug Downey, and Capt. Edward Marchand. Section V.E. of this document consists of the text of "Enhanced Biodegradation through Soil Venting," by R. E. Hinchee, D. C. Downey, R. R. Dupont, and M. Arthur, an unpublished report submitted to AFESC by Battelle-Columbus. Copies of the unpublished Appendices J and K are available from the authors at ORNL or the Chemical/Physical Treatment Technology Area Manager, HQ AFESC/RDVW, Tyndall AFB, Florida.

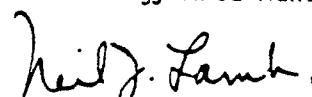
The authors are grateful for the assistance and cooperation of many people at Hill AFB, including Alan Delpias, Capt Edward Heyse, Robert Elliott, and Jay Gupta of the Directorate of Environmental Management and Don Camp, Joe Anderson, and the remainder of the Building 914 staff. We acknowledge the excellent support received from the Utah Water Research Laboratory of Utah State University (USU). Ryan Dupont coordinated the USU work, and, with Bill Doucette and students Maj. Ross Miller and Joy Emory, provided analytical support throughout the demonstration and system monitoring for five months. The authors thank Neil Hutzler of Michigan Technological University for constructive editing of these reports, and his student, John Gierke, for assistance during the pilot test. System design guidance was obtained from our consultants, James Malot of Terra Vac, Inc., and Nancy Metzger and Michael Corbin of R. F. Weston, Inc.

This document has been reviewed by the Public Affairs Office and is releasable to the general public, including foreign nationals.

This document has been reviewed and is approved for publication.

  
EDWARD G. MARCHAND, Capt, USAF, BSC  
Chemical/Physical Treatment  
Technology Area Manager

  
FRANK P. GALLAGHER III, Col, USAF  
Director, AF Civil Engineering  
Laboratory

  
NEIL J. LAMB, Col, USAF, BSC  
Chief, Environics Division

## TABLE OF CONTENTS

Section	Title	Page
I	INTRODUCTION .....	1
	A. OBJECTIVES .....	1
	B. BACKGROUND .....	2
	1. Description of Technology .....	2
	2. History of Site .....	5
	C. SCOPE .....	10
	1. Overview of Tests Conducted .....	10
	2. Chronology of Site Activities .....	11
	3. Report Organization .....	12
II	METHODOLOGY .....	13
	A. DRILLING .....	13
	B. LOGGING OF BOREHOLES .....	13
	C. SOIL SAMPLING AND HANDLING .....	14
	1. Excavation Samples .....	14
	2. Borehole Sample Collection .....	14
	3. Sample Handling .....	15
	D. SOIL CHARACTERIZATION .....	16
	1. Moisture Content .....	16
	2. Bulk Density .....	16
	3. Particle Size Analysis .....	16
	E. NEUTRON ACCESS TUBES .....	17
	1. Installation .....	17
	2. Calibration .....	17
	F. SOIL CHEMICAL ANALYSIS .....	18
	1. Petroleum Hydrocarbon Screening .....	18
	2. Laboratory Hydrocarbon Analysis .....	19
	3. Benzene/Toluene/Xylene .....	19



# TABLE OF CONTENTS (CONTINUED)

Section	Title	Page
	G. GROUNDWATER ANALYSIS .....	20
	1. Sampling and Handling .....	20
	2. Analysis .....	20
	H. GAS FLOW RATES .....	20
	1. Orifice Plates .....	20
	2. Rotameter .....	21
	3. Velocity Meters .....	22
	I. GAS ANALYSES .....	22
	1. Hydrocarbons by GC Analysis .....	22
	2. Hydrocarbons by Continuous Analysis .....	23
	3. Explosive Gas Monitor .....	24
	4. Carbon Dioxide .....	25
	5. Oxygen .....	25
	6. Humidity .....	25
III	SITE CHARACTERIZATION .....	26
	A. GEOHYDROLOGY .....	26
	1. Stratigraphy .....	26
	2. Soil Characteristics .....	32
	3. Moisture .....	34
	B. HYDROCARBON CONTAMINATION .....	34
	1. Total Hydrocarbons .....	34
	2. Benzene, Toluene, and Xylene .....	39
	3. Hydrocarbon Boiling Ranges .....	39
	C. INITIAL HYDROCARBON MASS .....	41
	1. Vertical Vent Area .....	46
	2. Area Beneath Tank Excavation .....	46
	3. Pile .....	51
	4. Totals .....	51

# TABLE OF CONTENTS (CONTINUED)

Section	Title	Page
IV	PILOT STUDIES .....	54
	A. INTRODUCTION .....	54
	B. SINGLE VENT PILOT TEST .....	55
	1. System Design .....	55
	2. Single-Vent Test System Operation .....	63
	3. Single-Vent Test Results .....	64
	C. COLUMN TEST .....	72
	1. Materials and Method .....	72
	2. Column Test Results .....	74
	D. <i>IN SITU</i> PERMEABILITY TESTS .....	74
	1. Transient Recovery Procedures .....	74
	2. Steady State Procedures .....	75
	3. Summary of <i>In Situ</i> Permeability Testing .....	79
	E. FLOW MODELING .....	79
	F. DISCUSSION .....	80
	1. Projected System Behavior .....	80
	2. Application of Flow Modeling to Full-Scale Vent Spacing .....	85
	G. CONCLUSIONS OF PILOT TESTING .....	88
V	FULL-SCALE VENTING DEMONSTRATION .....	90
	A. INTRODUCTION .....	90
	B. DESCRIPTION OF EQUIPMENT .....	90
	1. Vertical Vent Subsystem .....	90
	2. Lateral Vent Subsystem .....	101
	3. Excavated Soil Pile Subsystem .....	105
	4. Blower/Emission Control System .....	106

# TABLE OF CONTENTS (CONTINUED)

Section	Title	Page
C.	SYSTEM OPERATION .....	116
1.	Modes of Operation .....	116
2.	Chronology of Operation .....	118
D.	RESULTS OF HYDROCARBON REMOVAL BY VOLATILIZATION .....	118
1.	Mass Removal .....	118
2.	Soil Gas Concentrations .....	121
3.	Extracted Gas Hydrocarbon Concentration .....	127
4.	Extracted Gas Hydrocarbon Distribution .....	129
5.	Comparison with Equilibrium Model .....	134
6.	Discussion .....	137
E.	BIOACTIVITY .....	139
	<i>Enhanced Biodegradation through Soil Venting by R. E. Hinchee, D. C. Downey, R. R. Dupont, and M. Arthur</i>	
1.	Background .....	140
2.	Scope/Approach .....	141
3.	Microbial Characterization .....	141
4.	Field Studies .....	141
5.	Bench-Scale Studies .....	155
6.	Conclusions of Biodegradation Studies .....	159
7.	Recommendations .....	160
8.	Additional Observations by ORNL Staff .....	161
F.	SOIL MOISTURE .....	162
G.	FLOW TESTS AND MODELING .....	163
1.	Flow Test Description .....	166
2.	Flow Test Results .....	166
3.	Air Flow Modeling .....	169
H.	ENHANCEMENT OF REMOVAL BY HEATING .....	170
1.	Concept .....	170
2.	Description of Test .....	173
3.	Results .....	174

# TABLE OF CONTENTS (CONCLUDED)

Section	Title	Page
	4. Discussion .....	177
	5. Conclusions of Heat Injection Test .....	182
I.	EMISSIONS CONTROL BY CATALYTIC OXIDATION .....	183
	1. Operation .....	183
	2. Conversion Results .....	184
	3. Propane Consumption .....	186
	4. Conclusions of Emissions Control Monitoring .....	186
J.	EFFECTIVENESS OF SITE TREATMENT .....	190
	1. Post-Venting Soil Analyses .....	190
	2. Effectiveness of Hydrocarbon Removal .....	192
	3. Factors Affecting hydrocarbon Removal .....	193
	4. Comparison of Total Hydrocarbon Removal Determined from Soil and Off-Gas Measurements .....	197
K.	COSTS .....	200
VI	CONCLUSIONS .....	204
VII	RECOMMENDATIONS .....	207
VIII	REFERENCES .....	209
APPENDIX		
A	PRE-VENTING SITE CHARACTERIZATION .....	213
B	COORDINATES OF VENTS, PRESSURE MONITORING POINTS, AND NEUTRON ACCESS TUBES .....	249
C	EXTRACTED GAS ANALYSES .....	253
D	ORNL CALCULATIONS OF BIODEGRADATION .....	259
E	<i>IN SITU</i> MOISTURE CONTENT MEASUREMENTS .....	263
F	SUMMARY OF FLOW TESTS .....	269
G	POST-VENTING CHARACTERIZATION .....	277
H	TABLE OF CONTENTS OF APPENDICES J AND K (UNPUBLISHED) .....	307

## LIST OF FIGURES

Figure	Title	Page
1	Conceptual Diagram of <i>In Situ</i> Soil Venting .....	3
2	Schematic Diagram of Regional Hydrogeology in Vicinity of Hill AFB. ....	6
3	Geologic Log of Water Supply Well Located Approximately 500 Feet (152 meters) South of Building 914 Fuel Spill Site .....	7
4	Soil Vapor Concentration Contours Determined During Science Applications International Corporation (SAIC) Soil Vapor Study .....	9
5	Locations of All Borings Drilled at the Hill AFB Building 914 Fuel Spill Site During the Soil Venting Demonstration from November 1987 through October 1989 .....	28
6	Geologic East-West Cross-Sections Across the Northern and Central Portions of the Spill Site, Based on Logs from Borings Drilled During the Soil Venting Demonstration Project. ....	29
7	Geologic East-West Cross-Section across the Southern Portion of the Spill Site, and North-South Cross-Section Across the Western End of the Site .....	30
8	Geologic North-South Cross-Sections Across the Center and Eastern End of the Spill Site .....	31
9	Fence Diagram of Stratigraphic Features at the Building 914 Fuel Spill Site, Based on Geologic Cross-Sections .....	33
10	Locations of Borings BH41-44 at the Fuel Spill Site, Drilled for Characterization of the Extent of Eastward and Downward Migration of Fuel Contamination .....	37
11	Locations of Vent Well and Pressure Monitoring Point Borings Which Were Sampled During Pre-Venting Characterization .....	38
12	Locations of Pre- and Post-Venting Borings in the Soil Pile .....	40
13	Proportions of Hydrocarbons in Fractions Identified by Apparent Carbon Number in Representative Samples from Pre-Venting Borings V4, V15, and E from the Vertical Vent Area .....	42
14	Proportions of Hydrocarbons in Fractions Identified by Apparent Carbon Number in Representative Samples from Pre-Venting Borings V11 and E From the Vertical Vent Area .....	42
15	Proportions of Hydrocarbons in Fractions Identified by Apparent Carbon Number in Representative Samples from Pre-Venting Borings BH31 and BH41 From the Vertical Vent Area .....	43
16	Comparison of Hydrocarbon Profile From a Sample From Boring V2 With a Profile (E) Representative of Most of the Vertical Vent Samples ....	43
17	Comparison of Gas Chromatographic Scans of Hydrocarbon Extracts From Boring V2 With a Scan (E) Representative of Most of the Vertical Vent Samples .....	44
18	Proportions of Hydrocarbons in Fractions Identified by Apparent Carbon Number in Representative Samples From Sub-Tank Excavation Borings BH5, BH16, and BH26 .....	45

# LIST OF FIGURES (CONTINUED)

Figure	Title	Page
19	Comparison of Hydrocarbon Profile From a Sample From Pile Borings P2 and P5 With a Profile (E) Representative of Most of the Vertical Vent Samples . . . . .	45
20	Schematic Diagram of Sub-Areas at the Vertical Vent Area of the Spill Site, Delineated For Determination of Total Mass of Residual Hydrocarbons . . . . .	47
21	Schematic Diagram of Sub-Areas at the Sub-Tank Excavation Area of the Spill Site, Delineated for Determination of Total Mass of Residual Hydrocarbons . . . . .	50
22	Schematic Diagram of Sub-Volumes of the Soil Pile Area of the Spill Site, Delineated for Determination of Total Mass of Residual Hydrocarbons . . . . .	52
23	Position and Labeling of Monitoring Wells in Single Vent Pilot Test . . . . .	56
24	Detail of Vent Well Installation . . . . .	58
25	Vapor/Pressure Monitoring Well Installation . . . . .	59
26	<i>In Situ</i> Soil Venting Single Vent Test System . . . . .	60
27	Transient Pressure Response - Single Vent Test, Extraction Rate - 0.094 Standard m <sup>3</sup> /Second, Monitoring Point Distance - 3.0 Meters . . . . .	66
28	Transient Pressure Response - Single Vent Test, Extraction Rate - 0.094 m <sup>3</sup> /Second, Monitoring Point Distance - 6.1 Meters. . . . .	66
29	Transient Pressure Response - Single Vent Test, Extraction Rate - 0.094 m <sup>3</sup> /Second, Monitoring Point Distance - 9.1 Meters . . . . .	66
30	Pressure Contours During Pilot Test . . . . .	68
31	Single Vent Test Vacuum Requirements . . . . .	70
32	THA Response . . . . .	71
33	Schematic Diagram of Equipment and Installation Used to Conduct Transient Air Permeability Tests in Pilot Test Pressure Monitoring Wells . . . . .	76
34	Transient Pressure Data and Fit to Type Curve for Test of Monitoring Well 34 . . . . .	77
35	Schematic Diagram of Equipment and Installation Used to Conduct Steady-State Air Permeability Tests in Shallow Boreholes . . . . .	78
36	Comparison of Observed and Modeled Air Pressure in the Vicinity of the 4.25 m <sup>3</sup> /Minute Single Vent Test With a Constant Pressure Boundary at Land Surface . . . . .	81
37	Comparison of Observed and Modeled Air Pressure in the Vicinity of the 4.25 m <sup>3</sup> /Minute Single Vent Test With a No-Flow Boundary at Land Surface . . . . .	81
38	Comparison of Single Vent Test and Column Test Gas Concentration Results . . . . .	83

# **LIST OF FIGURES** **(CONTINUED)**

Figure	Title	Page
39	Extracted Gas Concentration Estimates - Extrapolation of Column Test and Raoult's Law Equilibrium Model . . . . .	84
40	Variation of Flux With Distance for Single Vent Operation With Surface Barrier . . . . .	87
41	Variation of Flux With Distance for Single Vent Operation With No Surface Barrier . . . . .	87
42	Conceptual Design of <i>In Situ</i> Soil Venting Demonstration System at Hill AFB . . . . .	91
43	Vertical Vent System Layout . . . . .	92
44	Position of Boreholes in Vertical Vent System . . . . .	94
45	Schematic Drawing of Pressure Probe Design and Installation . . . . .	96
46	Vent Head Construction . . . . .	98
47	Schematic Drawing of Neutron Access Tube Design and Installation . . . . .	100
48	View of Lateral Vent System During Installation . . . . .	102
49	Lateral Vent System Side View . . . . .	103
50	Lateral System Soil Gas Monitoring Probe . . . . .	104
51	Schematic of Blower/Emission Control System . . . . .	107
52	View of Blower/Emission Control System . . . . .	108
53	Piping Connecting Vents to Blower/Emission Control System . . . . .	109
54	Fluidized Bed Catalytic Oxidizer . . . . .	111
55	Fixed-Bed Catalytic Oxidizer . . . . .	114
56	Fixed-Bed Oxidizer Catalyst Module . . . . .	115
57	Hydrocarbon Removal by Volatilization - Cumulative Removal as a Function of Time . . . . .	122
58	Hydrocarbon Removal - Cumulative Removal as a Function of Cumulative Gas Volume Extracted . . . . .	122
59	Soil Gas Hydrocarbon Contours (ppmv) 2 February 1989 . . . . .	123
60	Soil Gas Hydrocarbon Contours (ppmv) 3 March 1989 . . . . .	123
61	Soil Gas Hydrocarbon Contours (ppmv) 2 April 1989 . . . . .	124
62	Soil Gas Hydrocarbon Contours (ppmv) 10 June 1989 . . . . .	124
63	Soil Gas Hydrocarbon Contours (ppmv) 12 August 1989 . . . . .	125
64	Soil Gas Hydrocarbon Contours (ppmv) 7 October 1989 . . . . .	125
65	Variation of Hydrocarbon Concentration - THA and GC Samples . . . . .	128
66	Variation of Hydrocarbon Concentration in THA and GC Samples, Semi-Log Representation . . . . .	128
67	Variation of Hydrocarbon Concentration in THA and GC Samples, Logarithmic Representation . . . . .	129
68	Gas Chromatogram of Extracted Gas Sample, 6 January 1989 . . . . .	130
69	Gas Chromatogram of Extracted Gas Sample, 1 March 1989 . . . . .	131
70	Gas Chromatogram of Extracted Gas Sample, 26 May 1989 . . . . .	132
71	Gas Chromatogram of Extracted Gas Sample, 21 August 1989 . . . . .	133

# LIST OF FIGURES (CONTINUED)

Figure	Title	Page
72	Variation of Hydrocarbon Distribution in Extracted Gas Throughout Demonstration .....	135
73	Comparison of Model with Hydrocarbon Concentration Results; Semi-Log Representation .....	138
74	Comparison of Model With Hydrocarbon Concentration Results; Logarithmic Representation .....	138
75	Comparison of Model to Results of Hydrocarbon Composition .....	139
76	Vertical Distribution of Total and Hydrocarbon Degrading Microorganisms at Hill AFB, Utah, August and October 1988 .....	142
77	Isotopic Content of Off-Gases Collected from Hill AFB, Utah, and Various Other Environmental Forms of Carbon .....	145
78	Variation of Oxygen and Carbon Dioxide Concentrations in Extracted Gas With Time for the Period 18 December to 1 April 1989 .....	147
79	Contribution of Biodegradation to JP-4 Remediation at the Hill AFB, Utah, Venting Site, 18 December 1988 to 1 April 1989 .....	148
80	Oxygen Concentrations in Soil Gas on 7 December 1988 Prior to Any Venting .....	149
81	Oxygen Concentrations in Soil Gas on 19 December 1988 at the Initiation of the First <i>In Situ</i> Respiration Test .....	149
82	Oxygen Concentrations in Soil Gas on 22 December 1988 at the Conclusion of the First <i>In Situ</i> Respiration Test .....	150
83	Oxygen Concentrations in Soil Gas on 13 January 1989 at the Initiation of the Second <i>In Situ</i> Respiration Test .....	150
84	Oxygen Concentrations in Soil Gas on 18 January 1989 at the Completion of the Second <i>In Situ</i> Respiration Test .....	151
85	Oxygen Concentrations in Soil Gas on 26 May 1989 at the Initiation of the Third <i>In Situ</i> Respiration Test .....	151
86	Oxygen Concentrations in Soil Gas on 9 June 1989 at the Conclusion of the Third <i>In Situ</i> Respiration Test .....	152
87	The Results of the First <i>In Situ</i> Respiration Test at Monitoring Point Y (65 Feet Below Land Surface), 19 Dec 1989 .....	152
88	The Results of the Three Successive <i>In Situ</i> Respiration Tests at Monitoring Point Y (65 Feet Below Land Surface) .....	153
89	The Results of the Three Successive <i>In Situ</i> Respiration Tests at Monitoring Point M (25 Feet Below Land Surface) .....	153
90	JP-4 Hydrocarbon (HC), O <sub>2</sub> and CO <sub>2</sub> Concentrations 9 June 1989 in the Monitoring Points at the Conclusion of the Third <i>In Situ</i> Respiration Test .....	154
91	JP-4 Hydrocarbon (HC), O <sub>2</sub> and CO <sub>2</sub> Concentrations 9 June 1989, in the Vents at Conclusion of the Third <i>In Situ</i> Respiration Test .....	155
92	Results of Bench Scale Treatability Studies .....	158



# **LIST OF FIGURES (CONCLUDED)**

Figure	Title	Page
93	Results of Dead Control for Bench Scale Treatability Studies .....	159
94	Comparison of Hydrocarbon Removal by Biodegradation and Volatilization .....	162
95	Depth Profile of Moisture Content in Neutron Access Tube (NA1) Installed in Vented Area Without Surface Cover, June 1989 .....	164
96	Depth Profile of Moisture Content in Neutron Access Tube (NA2) Installed in Vented Area With Surface Cover, June 1989 .....	164
97	Depth Profile of Moisture Content in Neutron Access Tube (NA3) Installed Beyond the Vented Area, June 1989 .....	165
98	Depth Profiles of Moisture Content Recorded in NA1 at Four Dates Prior To, During, and Following the Venting Demonstrations .....	165
99	Depth-Averaged Pressure Contours - Flow Test 3 .....	167
100	Depth-Averaged Pressure Contours - Flow Test 4 .....	167
101	Depth-Averaged Pressure Contours - Flow Test 15 .....	168
102	Depth-Averaged Pressure Contours - Flow Test 22 .....	168
103	Equilibrium Removal Curves for JP-4 Standard Showing the Effect of Temperature .....	171
104	Schematic of Heat Injection Test System .....	173
105	Positions of Thermocouples for Heat Injection Test .....	175
106	Variation of Soil Temperature Measurements During Heat Injection Test ...	175
107	Areal Distribution of Temperatures at Three Times During Heat Injection Test - 16 August 1989, 29 August 1989, and 21 September 1989 ....	176
108	Hydrocarbon Levels in Extracted Gas During Heat Injection Test .....	178
109	Calculation of Removal Enhancement by Heating .....	178
110	Possible Vent Configurations for Future Heat Injection Tests .....	180
111	Destruction Efficiency of Fixed-Bed Catalytic Oxidizer as a Function of Inlet Temperature .....	187
112	Destruction Efficiency of Fluidized-Bed Catalytic Oxidizer as a Function of Outlet Temperature .....	187
113	Destruction Efficiency of Fluidized-Bed Catalytic Oxidizer as a Function of Inlet Organic Concentration .....	188
114	Inlet and Outlet Gas Concentration and Composition for Oxidizers (22 June 1989) .....	188
115	Location of Borings (Identified by the Designation "V_A," "V_B," or "V_C") Installed for Post-Venting Characterization in the Vertical Vent Area .....	191
116	Regression of Measured Hydrocarbon Content (mg/kg) Against Moisture Content for the Suite of Post-Venting Soil Samples from Both the Pile and Vertical Vent Area Borings .....	196

## LIST OF TABLES

Table	Title	Page
1	CHRONOLOGY OF MAJOR SITE ACTIVITIES .....	11
2	SUMMARY OF BOREHOLES INSTALLED AT HILL AIR FORCE BASE BUILDING 914 FUEL SPILL SITE .....	27
3	SUMMARY OF LABORATORY ANALYSES FOR TOTAL HYDROCARBONS CONDUCTED DURING THE HILL AFB SOIL VENTING DEMONSTRATION .....	35
4	SUMMARY OF PRE-VENTING HYDROCARBON MASSES IN THE VERTICAL VENT AREA .....	48
5	PRE-VENTING FUEL MASS IN VERTICAL VENT AREA (ESTIMATED BY DYNAMIC GRAPHICS, INC.) .....	49
6	SUMMARY OF PRE-VENTING HYDROCARBON MASSES IN THE PILE .....	53
7	ISSV PILOT TEST CONDITIONS .....	64
8	SINGLE VENT TEST VACUUM DISTRIBUTIONS .....	67
9	EXTRACTION VENT PRESSURE DROP .....	69
10	SUMMARY OF GAS SAMPLING CONDITIONS .....	70
11	HYDROCARBON WEIGHT FRACTIONS IN GAS SAMPLES .....	73
12	CALCULATED EXTRACTION GAS CONCENTRATIONS .....	73
13	CALCULATION OF PERFORMANCE-BASED VENT SPACING .....	88
14	DETAILED CHRONOLOGY OF FULL-SCALE SYSTEM OPERATION ..	119
15	RESULTS OF ISOTOPIC ANALYSIS OF GASES COLLECTED IN JUNE 1989 .....	146
16	RESULTS OF <i>IN SITU</i> RESPIRATION TESTS WITH $R^2 > 0.60$ CONDUCTED AT HILL AIR FORCE BASE, UTAH .....	156
17	RESULTS OF JP-4 HYDROCARBON ANALYSIS AND MICROBIAL ENUMERATIONS ON SOILS FROM THE BENCH SCALE TREATABILITY TESTING .....	160
18	VARIATION OF VAPOR PRESSURE WITH TEMPERATURE FOR SELECTED FUEL COMPONENTS .....	171
19	ECONOMIC COMPARISON OF HEAT INJECTION CASES .....	182
20	SUMMARY OF RESULTS FOR FLUIDIZED-BED OXIDIZER .....	184
21	SUMMARY OF RESULTS FOR FIXED-BED OXIDIZER .....	185
22	AVERAGE PROPANE USAGE FOR CATALYTIC OXIDIZERS .....	189
23	PRE-VERSUS POST-VENTING HYDROCARBON MASS; UPPER 10 FEET OF SOIL ONLY .....	194
24	PRE-VERSUS POST-VENTING HYDROCARBON MASS: BIASED SAMPLES ONLY .....	195
25	CALCULATION OF HYDROCARBON REMOVAL BASED ON SOIL SAMPLES .....	197
26	COST ESTIMATE FOR REMEDIATION OF 26,000 GALLONS JP-4 SPILL BY SOIL VENTING .....	202

**LIST OF TABLES**  
(CONTINUED)

Table	Title	Page
A-1	SOIL CHARACTERISTICS: EXCAVATION BORINGS AND BORINGS 31 (V7) AND 41 .....	215
A-2	VARIABILITY OF MOISTURE CONTENT IN FIELD SOIL SAMPLE REPLICATES .....	217
A-3	MOISTURE CONTENT OF SAMPLES FROM VENT WELL BORINGS ..	218
A-4	MOISTURE CONTENT OF PRE-VENTING PILE SAMPLES .....	224
A-5	VARIABILITY OF FIELD AND LABORATORY ANALYTICAL REPLICATES .....	225
A-6	PRE-VENTING HYDROCARBON ANALYSES: BENEATH FUEL TANKS .....	227
A-7	PRE-VENTING HYDROCARBON ANALYSES: INITIAL EXPLORATORY BORINGS .....	229
A-8	PRE-VENTING HYDROCARBON ANALYSES: VERTICAL VENT BORINGS .....	231
A-9	PRE-VENTING HYDROCARBON ANALYSES: PILE .....	236
A-10	CONCENTRATIONS OF BENZENE, TOLUENE, AND XYLENES (BTX) IN SOIL SAMPLES COLLECTED DURING PRE-VENTING CHARACTERIZATION OF VERTICAL VENTED AREA .....	237
A-11	HYDROCARBON CONCENTRATIONS: EXCAVATION BOREHOLES ..	238
A-12	HYDROCARBON CONCENTRATIONS: BOREHOLES 31 (V7) AND 41 .....	242
A-13	JP-4 HYDROCARBON MASS PRESENT BENEATH THE EXCAVATED FUEL TANKS BEFORE VENTING .....	244
B-1	COORDINATES OF VENTS, PRESSURE MONITORING POINTS, AND NEUTRON ACCESS TUBES .....	251
C-1	SUMMARY OF GAS SAMPLING RESULTS (GC) .....	255
C-2	SUMMARY OF THA RESULTS .....	257
D-1	ORNL CALCULATIONS OF BIODEGRADATION .....	261
E-1	WATER CONTENT IN SOIL: NEUTRON ACCESS TUBE 1 .....	265
E-2	WATER CONTENT IN SOIL: NEUTRON ACCESS TUBE 2 .....	266
E-3	WATER CONTENT IN SOIL: NEUTRON ACCESS TUBE 3 .....	267
E-1	EXTRACTION RATES FROM EACH VENT .....	271
E-2	FLOW TEST RESULTS .....	272
G-1	POST-VENTING HYDROCARBON ANALYSES: BORINGS FROM VERTICAL VENT AREA .....	279
G-2	POST-VENTING HYDROCARBON ANALYSES: PILE .....	282
G-3	POST-VENTING SAMPLES ANALYZED FOR BENZENE, TOLUENE, AND XYLENES (BTX) .....	283
G-4	JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING .....	286

LIST OF TABLES  
(CONCLUDED)

Table	Title	Page
G-5	JP-4 MASS BALANCE: EXCAVATED SOIL PILE, PRE- AND POST-VENTING .....	287
G-6	RESULTS OF ANALYSIS FOR PETROLEUM DISTILLATE CONSTITUENTS IN GROUNDWATER FROM MONITORING WELL RST-1, OCTOBER 1989 .....	301
H-1	TABLE OF CONTENTS OF APPENDICES J AND K (UNPUBLISHED) .....	309

## LIST OF ABBREVIATIONS

AFB	Air Force Base
AFESC	Air Force Engineering and Services Center
API	American Petroleum Institute
BLS	Below Land Surface
BTX	Benzene, Toluene, and Xylenes
cm	Centimeter
CO <sub>2</sub>	Carbon Dioxide
CV	Coefficient of Variation
FID	Flame Ionization Detector
FM	Factory Mutual
ft <sup>3</sup>	Cubic Feet
GC	Gas Chromatograph
Hg	Mercury
hp	Horsepower
ID	Inside Diameter
IRI	Industrial Risk Insurer
ISSV	<i>In situ</i> Soil Venting
kg	Kilograms
kW	Kilowatt
LEL	Lower Explosive Limit
µg/liter	Micrograms per Liter
µL	Microliter
mg	Milligrams
mL	Milliliter
mm	Millimeters
MSA	Mine Safety Appliances
MSL	Mean Sea Level
m <sup>2</sup>	Meters Squared
m <sup>3</sup>	Cubic Meters
m <sup>3</sup> /minute	Cubic Meters per Minute
m <sup>3</sup> /second	Cubic Meters per Second
O <sub>2</sub>	Oxygen
ORNL	Oak Ridge National Laboratory
OD	Outside Diameter
ppmv	Parts-per-Million-by-Volume
psig	Pounds per Square Inch Gauge
PVC	Poly Vinyl Chloride
SAIC	Science Applications International Corporation
scfm	Standard Cubic Feet per Minute
scmm	Standard Cubic Meters per Minute
SE	Standard Error
SVO	Semivolatile Organics
TCAAP	Twin Cities Army Ammunitions Plant
TCE	Trichloroethylene
THA	Total Hydrocarbon Analyzer

---

LIST OF ABBREVIATIONS  
(CONCLUDED)

USATHAMA	United States Army Toxic and Hazardous Materials Agency
USEPA	United States Environmental Protection Agency
USU	Utah State University
UWRL	Utah Water Research Laboratory
VOA	Volatile Organics Analysis
VOC	Volatile Organic Compound

## LIST OF SYMBOLS

(Dimensions are given in terms of mass (M), length (L), time (t), temperature (T), and moles (mol).)

$a$	empirical constant in Antoine equation, (dimensionless)
$b$	empirical constant in Antoine equation, (T)
$B$	volume of acid for sample endpoint titration, ( $L^3$ )
$c$	empirical constant in Antoine equation, (T)
$C$	hydrocarbon concentration in soil, ( $M M^{-1}$ )
$C_{in}$	hydrocarbon concentration in inlet gas, ( $M L^{-1}$ )
$C_o$	discharge coefficient, (dimensionless)
$CO_2-C$	mass of carbon from carbon dioxide generation, (M)
$E$	equivalent mass of carbon in carbon dioxide, ( $M mol^{-1}$ )
$Eff$	destruction efficiency, (dimensionless)
$g_c$	gravity correction factor for American engineering units, (dimensionless)
$h$	vent depth, (L)
$k$	air permeability of soil, ( $L^2$ )
$K$	oxygen utilization first order rate constant, ( $t^{-1}$ )
$N$	acid normality, ( $mol L^{-3}$ )
$N_i$	moles of component $i$ , (mol)
$P$	absolute pressure, ( $M L^{-1} t^{-2}$ )
$P_i$	partial pressure of component $i$ , ( $M L^{-1} t^{-2}$ )
$P_i^{sat}$	vapor pressure of component $i$ , ( $M L^{-1} t^{-2}$ )
$P_s$	standard pressure, ( $M L^{-1} t^{-2}$ )
$Q$	volumetric gas flow rate, ( $L^3/t$ )
$Q_s$	volumetric gas flow rate at standard conditions, ( $L^3/t$ )
$r_s$	vent spacing, (L)
$R$	gas constant, ( $M L^2 t^{-2} T^{-1} mol^{-1}$ )
$R_{sample}$	isotopic ratio of $^{13}C$ to $^{12}C$ in sample, (dimensionless)
$R_{std}$	standard isotopic ratio of $^{13}C$ to $^{12}C$ , (dimensionless)
$R^2$	correlation coefficient, (dimensionless)
$S_i$	pipe cross-sectional area, ( $L^2$ )
$S_o$	orifice cross-sectional area, ( $L^2$ )
$t$	time, (t)
$T$	absolute temperature, (T)
$T_i$	inlet temperature, (T)
$T_o$	outlet temperature, (T)
$V$	volume of acid for sample endpoint titration, ( $L^3$ )
$V_i$	average velocity of inlet gas, ( $L/t$ )
$x$	moisture content, ( $M M^{-1}$ )
$x_i$	liquid phase mole fraction of component $i$ , (dimensionless)
$y$	hydrocarbon concentration in soil, ( $M M^{-1}$ )
$z$	deviation from standard isotopic ratio, (dimensionless)
$\Delta P$	pressure drop, ( $M L^{-1} t^{-2}$ )
$\theta_{dw}$	moisture content on dry weight basis, ( $M M^{-1}$ )
$\rho$	gas density, ( $M L^{-3}$ )

# FIELD DEMONSTRATION OF *IN SITU* SOIL VENTING AT HILL AIR FORCE BASE JP-4 JET FUEL SPILL SITE

## SECTION I

### INTRODUCTION

#### A. OBJECTIVES

Over 4,000 Air Force sites are known or suspected to have contaminated groundwater and soil. The most common contaminants are fuels and chlorinated solvents. Since many of these contaminants are volatile or have volatile components, a relatively inexpensive method for aiding the cleanup of these sites is an innovative technology known as *in situ* soil venting (ISSV). This process for remediation of volatile organic compound (VOC) contamination of soil involves passing large volumes of air through the subsurface soil, thereby disrupting the equilibrium existing between the contaminants on the soil and in the vapor and causing volatilization and transport of the VOCs from the ground into the air stream.

Oak Ridge National Laboratory (ORNL) was contracted by the Air Force Engineering and Services Center (AFESC) to perform a full-scale demonstration of *in situ* soil venting at an Air Force site. The two main objectives of this research effort were (1) determine the efficiency of *in situ* soil venting for removal of fuel from unsaturated soils; and (2) collect design, operating, and cost data for use in implementation of *in situ* soil venting at other Air Force sites.

To meet these objectives, a site selection decision was made after reviewing Installation Restoration Program reports, meeting with base personnel, and visiting several contaminated Air Force Base (AFB) sites. A site at Hill AFB, Utah, was chosen because of several favorable characteristics.

An initial characterization of the contaminated area at Hill AFB showed the site to be nearly ideal from a geohydrologic standpoint for application of soil venting technology. The initial report also indicated there was significant residual contamination that would be appropriate for demonstration of the technology. In addition, the Hill AFB site offered easy access, available utilities, and logistics support. Also, the Hill site allowed the opportunity to study multiple venting configurations.

After site selection, additional site characterizations, and pilot tests, a full-scale demonstration system was operated at the Hill AFB site. The system was designed and constructed by ORNL, after a design review by consultants (Mr. James Malot of Terra Vac, Inc., Ms. Nancy Metzger and Mr. Michael H. Corbin of R. F. Weston, Inc.) representing leading vendors of soil-venting systems. Site characterization before and after system operation allowed for evaluation of the effectiveness of the cleanup effort.



## B. BACKGROUND

### 1. Description of Technology

*In situ* soil venting, also referred to as *in situ* volatilization, *in situ* air stripping, and soil vapor extraction, is a promising technology for removal of volatile contaminant spills in unsaturated zone soils. A conceptual picture of ISSV is shown in Figure 1. In this technique, the soil is decontaminated in place by pulling air through the soil. Air removed from the soil by an extraction vent and vacuum blower may be resupplied passively by infiltration from the surface, or passively or forced through injection vents. The air flow sweeps out the soil gas, disrupting the equilibrium existing between hydrocarbons which are (1) sorbed on the soil, (2) dissolved in soil pore water, (3) present as a separate hydrocarbon phase, and (4) present as vapor. This causes volatilization of the contaminants and subsequent removal in the air stream. Depending on flow rate, contaminant type and concentration, and local environmental regulations, the extracted gas stream may be discharged directly to the atmosphere or sent to an emissions control device.

*In situ* soil venting has proven to be a cost-effective decontamination technology. It is extremely useful in decontaminating unsaturated zone soils, both in preventing the hazards caused by subsurface vapor movement and in removing the contaminants before they reach the groundwater. Soil venting may also be used in conjunction with pump-and-treat groundwater remediation techniques for complete cleanup of the soil and groundwater in cases where the hydrocarbons have reached the water table. A general summary of technical aspects of *in situ* soil venting, its applicability, and geohydrologic factors controlling its effectiveness is provided in Volume I. An abbreviated overview is given below.

*In situ* soil venting is generally applicable to spills of VOCs in permeable soils, although it has been reported to be successful in less permeable soils. Each site must be considered individually for the feasibility of application of the technique. Variables to be considered include (1) the size of the spill, (2) the type of contaminant, (3) geohydrological factors, and (4) regulatory issues such as emissions treatment and cleanup standards. In general, larger and/or deeper contaminated soil zones favor soil venting over excavation; although a size criteria may be waived when considering treatment of a site containing a building or other valuable structures. Contaminants having a vapor pressure of at least 0.5 millimeters (mm) mercury (Hg) (66 Pascals), or a dimensionless (i.e., mole fraction ratio) Henry's Law constant greater than 0.01 (Reference 1) are likely to be extracted at adequate rates. *In situ* soil venting is less easily applied to soils with complex stratification or soils of low permeability, although recent successful field tests have demonstrated removal in lower permeability soils (Reference 2).

Various design strategies of soil venting have been implemented, with most exhibiting promising results. The simplest designs include only vapor extraction vents, which may be adequate for remediation for the majority of sites. For deep contamination or for cases with free product on the water table, passive inlet vents may be included to direct air flow into the lower soil areas. Other systems include pressurized injection vents around the contamination area to increase flow rate and control. An impermeable surface barrier is often recommended to prevent rainwater infiltration and the short-circuiting of the air flow from the surface. Several different types of blowers have been used, the selection of which is dependent on site-specific factors such as size and soil permeability.

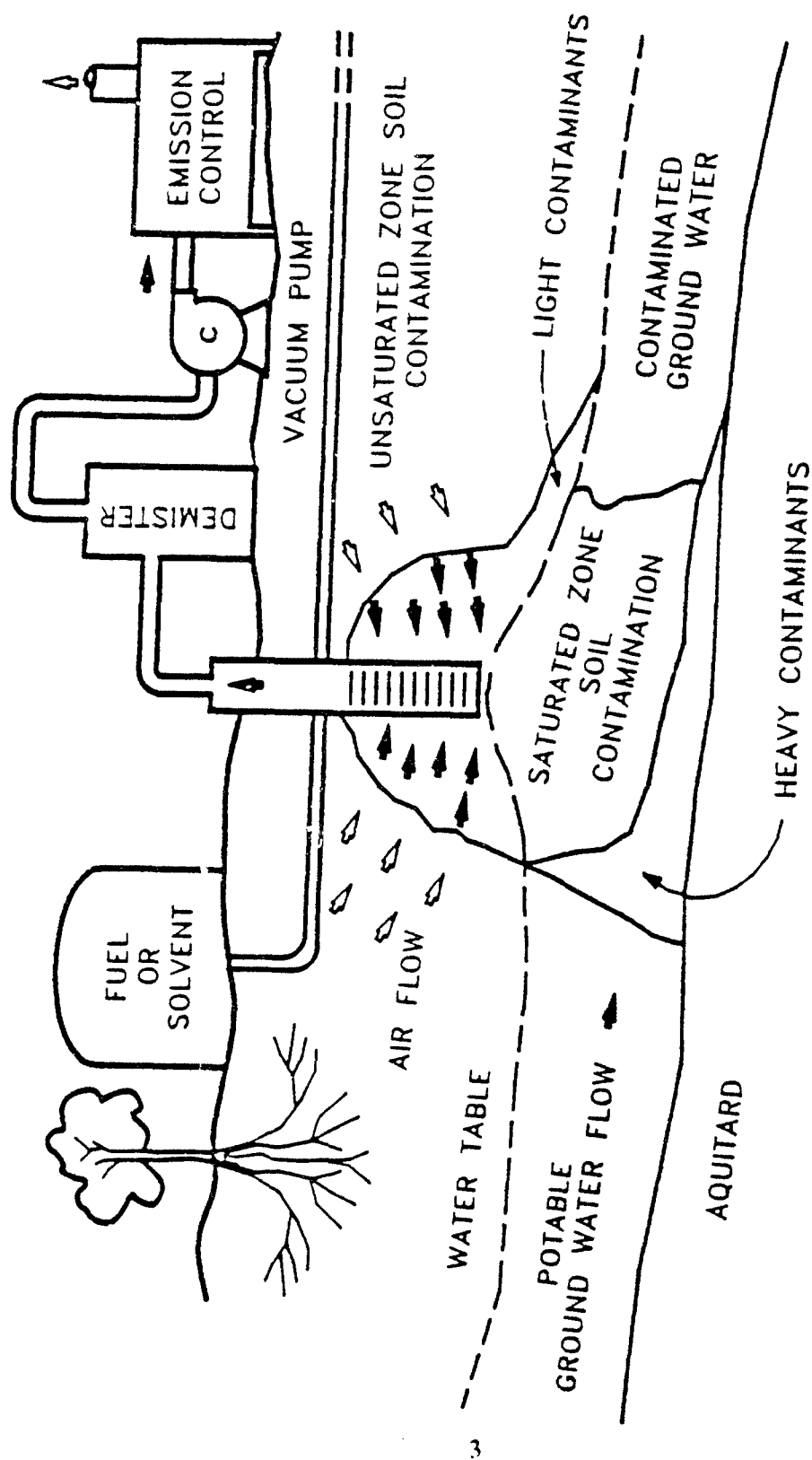


Figure 1. Conceptual Diagram of *In Situ* Soil Venting.

Specific site characterization data should be collected and a pilot system should be run at the site prior to full-scale design.

It may be difficult to predict the overall effectiveness of soil venting or any other *in situ* restoration technique because heterogeneity of soil structure and contamination location preclude measuring the initial mass present at a site. Factors influencing the effectiveness of soil venting include (1) amount and geometry of air flow, (2) nature of the contaminants, (3) geohydrology, (4) temperature, (5) moisture, and (6) aerobic bioactivity. In general, factors which increase contaminant removal rate are higher air flow through contaminated soil zones, contaminants of higher volatility, soils of simple stratification and high air permeability, higher temperatures, lower moisture content, and higher aerobic activity.

Although several successful applications have been reported in the literature, at the time that this project was initiated only two well-documented field studies of soil venting were available. Radian and Riedel Environmental Services performed a field test of soil venting for the American Petroleum Institute (References 3 and 4). They operated two sets of test wells in an existing gasoline spill which had reached the aquifer and was spread out in the capillary zone. During the 36-day test they operated at three flow rates, measuring pressure and concentration at several points in the soil. Effluent gas concentrations remained high (2000 to 4000 ppmv) throughout the test, demonstrating high removal rates, but also indicating that the flow rates were too low or the test duration too short to note long-term trends. The results also showed the effect of vapor recharge from the free product layer in the capillary zone and atop the water table. They concluded that soil venting is not only effective for removing hydrocarbons from the unsaturated zone soils, but also can be used in conjunction with conventional methods for aquifer restoration. However, the short test period and unchanging extraction rate did not allow evaluation of the variation of hydrocarbon yield with time or final removal capabilities.

Roy F. Weston, Inc., in conjunction with the US Army Toxic and Hazardous Materials Agency (USATHAMA), operated a pilot-scale soil venting test at a solvent dump site at the Twin Cities Army Ammunitions Plant (TCAAP) (Reference 5). The test included two systems: a large system in a highly contaminated zone and a smaller system in a less contaminated area. Results indicated soil venting is effective in removal of trichloroethylene, dichloroethylene, toluene, and other solvents from sandy soils. Effluent concentrations in the small system decreased rapidly with time, whereas the effluent from the large system remained at high concentrations throughout the test, again indicating a test system which was undersized for the schedule of the test. Due to the short term of the tests, it was not clear if the technology continues to be effective after extended operation has reduced contamination to some lower level. Empirical design relationships of vent pipe spacing and blower sizing for scale-up at the site were developed, and preliminary cost estimates of \$15 to \$20/yd<sup>3</sup> of soil treated were presented.

These studies provided much useful information for the successful application of soil venting; however, more information is necessary to design full-scale systems. Two important questions remained: (1) the long-term effectiveness of the technology and (2) its applicability to other contaminants or contaminant mixtures, such as JP-4 jet fuel. Also, information from a well-characterized system is needed to analyze factors controlling contaminant removal for optimization of the technology.

This study was undertaken to provide answers to these and other questions. A full-scale venting system was operated at the site of a JP-4 jet fuel spill site to determine the applicability of the technology to this widespread contaminant and to collect valuable field information for use in projecting design data, cost, and effectiveness of the technology to other sites. Volume II of this report is a guidance document which contains much of this practical information.

## 2. History of Site

On 9 January 1985, in the Building 914 area at Hill Air Force Base, Utah, approximately 27,000 gallons (102,000 liters) of jet fuel were spilled onto the ground after an automatic filling system malfunctioned and storage tanks overflowed. The fuel flowed into the area to the west of the tanks and infiltrated the soil throughout the area. No other spills have been reported in the area.

The site had been the subject of two earlier site characterizations, as well as characterization by ORNL. From the recommendations of the first study (Reference 6), a decision was made to remove the highly contaminated soil near the underground tanks and place the tanks in an aboveground concrete enclosure. The plans for the tank excavation were modified to include the testing of *in situ* soil venting technology described herein. Lateral vent pipes were installed in the ground beneath the tank excavation and the excavated soil was formed into a pile for venting.

### a. Site Geology

Hill Air Force Base is located on a terrace along the western foot of the Wasatch Mountains at an altitude of approximately 4750 to 4780 feet (1448 to 1457 meters) above mean sea level. The terrace on which the Base is located is one of several which were formed as near-shore sedimentary deposits of prehistoric Lake Bonneville, the remnant of which comprises present-day Great Salt Lake. These unconsolidated or weakly consolidated deposits are comprised of a series of interfingering lenticular or wedge-shaped strata of gravel, sand, silt, and clay extending to a depth of as great as 6000 to 9000 feet (1829 to 2743 meters) several miles to the west of the Base (Figure 2). The regional geology has been described in detail (Reference 7).

The Provo formation comprises the surface strata beneath the Base, and consists at the fuel spill site of medium to fine sands with thin interbedded layers of silty clay. Regionally these sands are underlain by clay layers, which extend to a depth of 600 feet (183 meters) below land surface (BLS) at a well located 500 feet (152 meters) south of the spill site (Figure 3).

Logs from observed hole cuttings for a series of 23 borings conducted in 1985 at the spill site by Rollins, Brown & Gunnell, Inc. describe a surface layer of brown silty sand about 4 feet (1.2 meters) thick, underlain by brown sand to a depth of 20 to 23 feet (6.1 to 7.0 meters) throughout the spill area west of the buried fuel tanks (Reference 6). Clay layers were reported between a depth of 23 feet (7.0 meters), extending with intermixed sand, to the depth of the deepest boring (42 feet - 12.8 meters).

Three borings were augered by Science Applications International (SAIC) in the northern portion of the spill area in June 1986. Logs from these borings generally show sand to a depth of 25 to 35 feet (7.6 to 10.7 meters), with occasional thin layers of clay above and discontinuous clay and silty clay stringers interspersed with sand below.

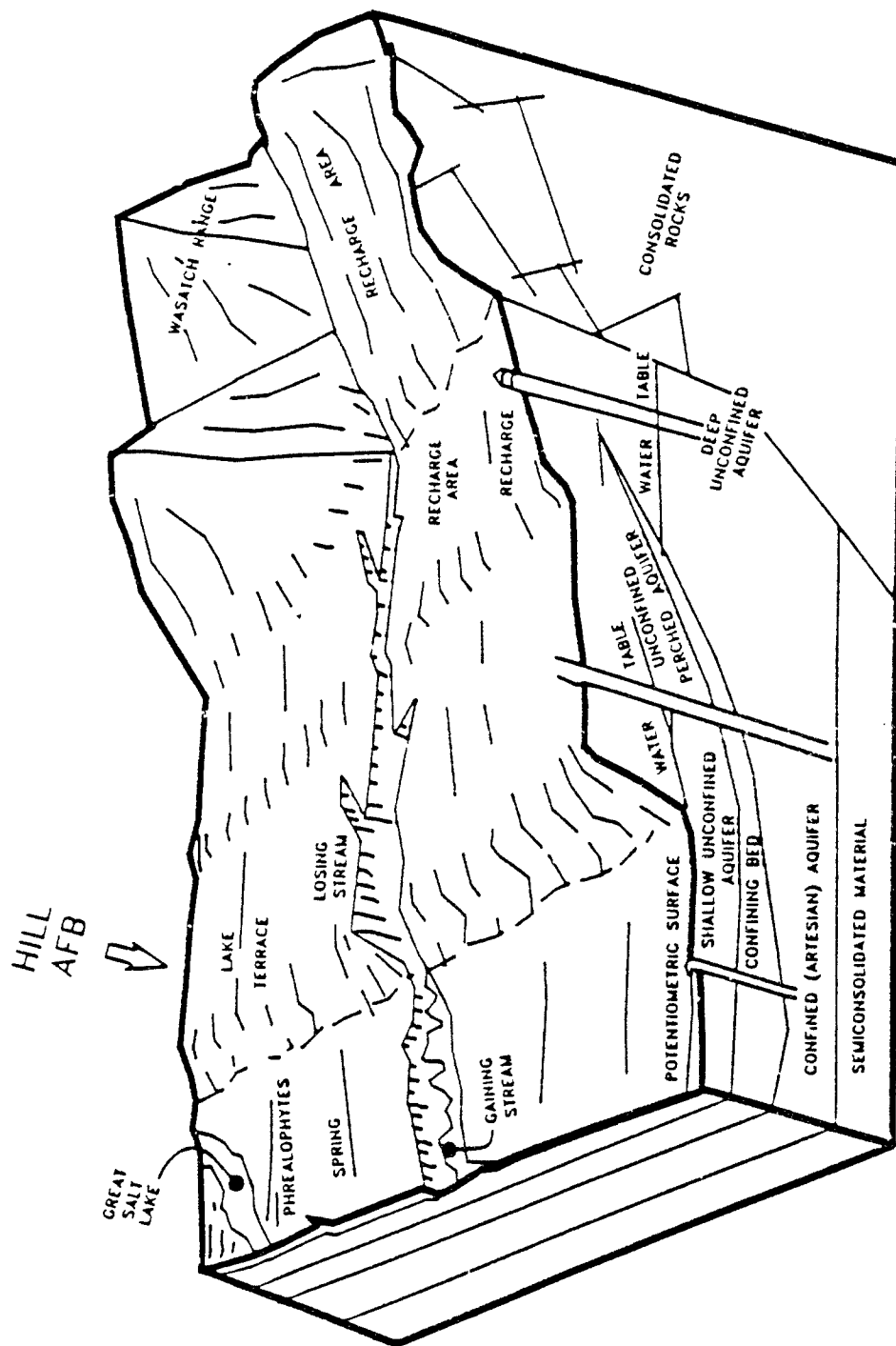


Figure 2. Schematic Diagram of Regional Hydrogeology in Vicinity of Hill AFB.

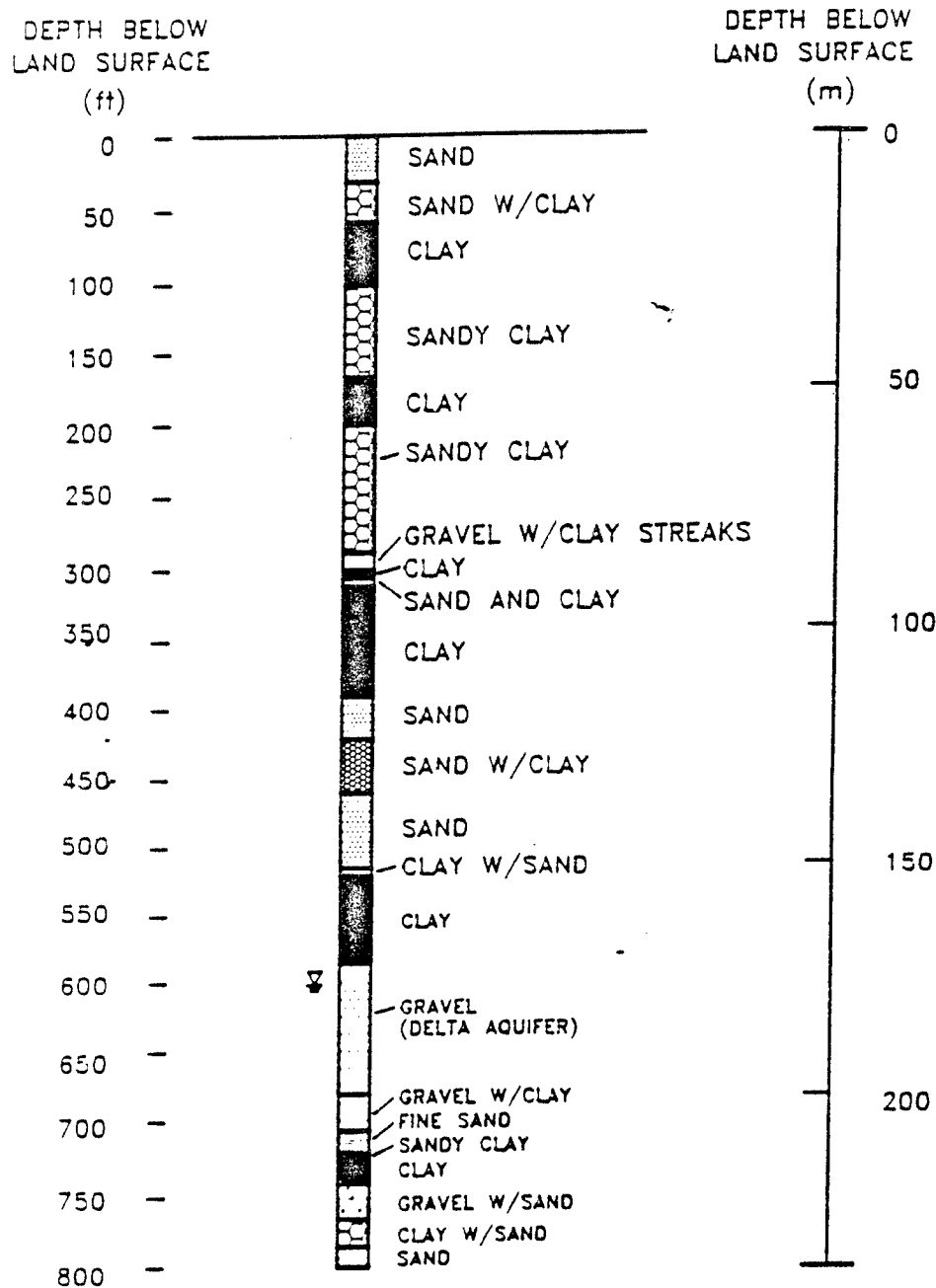


Figure 3. Geologic Log of Water Supply Well Located Approximately 500 feet (152 meters) South of Building 914 Fuel Spill Site. Source: Reference 6.

## **b. Site Hydrology**

The shallowest regional groundwater is an aquifer approximately 100 feet (30.5 meters) thick which underlies the spill site at a depth of about 600 feet (183 meters) BLS. The continuous water table, the Sunset aquifer, is at a depth of 300 feet (91.4 meters) BLS. Both aquifers are isolated from the surface by impermeable formations which produce artesian conditions in the area of the base.

Local perched groundwater is found above the clay layers which confine the regional aquifer. Rollins, Brown & Gunnell, Inc. encountered perched groundwater in one borehole near the fuel tanks at a depth of 32 feet (9.8 meters) BLS. During the SAIC drilling, perched water was encountered at a depth of 51 feet (15.5 meters) BLS in borehole RSA-2 on the western edge of the spill area, while water was present at a depth of approximately 57 feet (17.4 meters) BLS in monitoring well RST-1 in December 1987 (see Figure 4).

## **c. Distribution of JP-4 Contamination in the Soil**

(1) Soil Gas Analyses. A soil gas survey was conducted by SAIC at the spill site in 1986, with probes installed to a depth of 10 feet (3.0 meters). Fuel vapor profiles measured as total hydrocarbons determined from the analytical data are shown in Figure 4. Highest values extend from the point of fuel spillage west across the spill area, approximately along the path of fuel flow.

(2) Core Analyses. Analysis of cores from the borings conducted by Rollins, Brown & Gunnell, Inc. in 1985 showed residual fuel levels as high as 70,000 mg/kg in soils immediately adjacent to the tanks. The deepest fuel penetration observed at that time was 28 feet (8.5 meters) BLS in a borehole immediately west of the tanks. Concentrations of total hydrocarbons as high as 6200 mg/kg were detected in the upper 5 feet (1.5 meters) of soil throughout the spill area west of the tanks. Cores from boreholes near the present location of well RST-1 showed fuel residues as high as 15,770 mg/kg at a depth of 13 feet (4.0 meters) BLS. No fuel residues were detected in two borings conducted west of the fence, approximately 150 feet (46 meters) west of the fuel tanks, which bounds the fuel storage area.

Core analyses from the three borings conducted by SAIC in 1986 showed lower levels of residual fuel in the upper soil; the highest values obtained were 3700 mg/kg and 1200 mg/kg at depths of 0 and 19 feet (0 and 5.8 meters), respectively, in RST-1. Fuel odors were present throughout the RST-1 cores, and a level of 81 mg/kg was detected at the surface of the clay layer at 54 feet (16.5 meters) BLS. No residual fuel was detected in either of two temporary groundwater monitoring wells denoted RSA-1 or RSA-2 at any depth.

(3) Additional Site Characterization Prior to Venting System Installation. Due to uncertainties in site geology, hydrology and hydrocarbon distribution, further site characterization, consisting of a second soil gas survey and installation of three borings, was performed by ORNL before installation of the full-scale venting system. The purpose of the soil gas survey was to confirm the earlier fuel distribution data and to determine whether additional lateral fuel movement had occurred. The purpose of the drilling was to determine whether fuel had migrated to the east of the

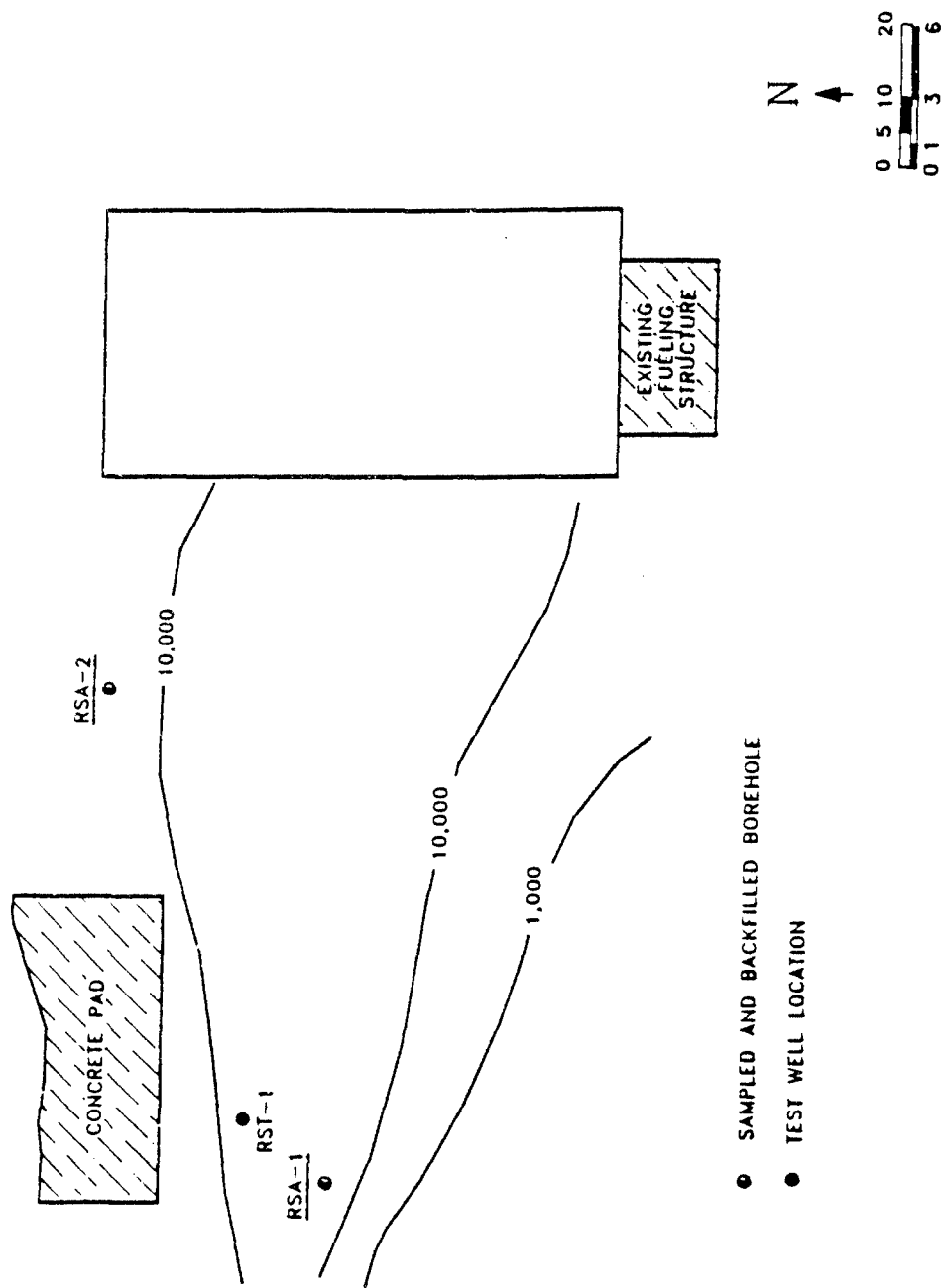


Figure 4. Soil Vapor Concentration Contours Determined During Science Applications International Corporation (SAIC) Soil Vapor Study. Vapor Concentrations in micrograms per liter ( $\mu\text{g}/\text{liter}$ ). Redrawn from SAIC (1988).



tanks through unsaturated clay layers or had cascaded down along the clay layers and infiltrated to a depth below 50 feet (15.2 meters).

A soil gas survey, conducted in September 1987, confirmed the general distribution of near-surface hydrocarbon concentrations determined by SAIC. No evidence for fuel contamination was found west of the fence on the western boundary of the spill area. The three borings drilled during June 1988 confirmed the presence of clay beneath the eastern portion of the site at a depth of 90 feet (27.4 meters) confirmed that fuel had not migrated to the east of the tank excavation, and confirmed that fuel had not penetrated into the subsurface clay layer.

## C. SCOPE

### 1. Overview of Tests Conducted

The *in situ* soil venting demonstration addressed in this study followed a staged implementation, as would be recommended for most applications of this technology. The three stages of the study were (1) site characterization, (2) pilot studies, and (3) full-scale demonstration. These phases are discussed in more detail below.

#### a. Phase 1: Site Characterization

Characterization of the site included gathering information from previous studies, soil gas analyses, and soil sampling at various points in the contaminated area. These activities took place between November 1987 and November 1988. Results of site characterization activities are presented in Section IV.

#### b. Phase 2: Pilot Studies

The pilot studies consisted of limited laboratory-scale column studies, development and conduction of *in situ* permeability tests, and a field pilot test involving operation of a single extraction vent. Column tests were performed during February 1988. The results of these tests are presented in Section IV.C. The single-vent test extraction at the Hill AFB site was conducted in January 1988. These tests and their results are presented in Section IV.B. of this report. *In situ* permeability tests were performed in December 1987 and again during July and September of 1988. These tests are described in detail in Section IV.D.

#### c. Phase 3: Full-Scale Demonstration

The vertical vents for the full-scale *in situ* soil venting demonstration were installed during August and September 1988. The piping and associated vacuum extraction equipment were constructed and/or installed from October through December 1988. After obtaining the required approvals from the appropriate regulatory agencies, operation of the full-scale system was started in December 1988. The full-scale system was operated nearly continuously through October 1989 using various vent configurations. During this period, hydrocarbon concentrations, removal rates, bioactivity, soil-moisture content, and various other parameters were monitored. Section V of this report contains the details and results obtained during full-scale operation.

## 2. Chronology of Site Activities

Table 1 lists the dates for the major activities performed in this demonstration effort.

TABLE 1. CHRONOLOGY OF MAJOR SITE ACTIVITIES

DATE	ACTIVITY
1-6 November 1987	Sampling for characterization of soil contamination in the excavation site done by ORNL Grand Junction, CO office. 14 holes sampled, 31 soil vapor probes placed in soil.
2-6 November 1987	Soil sampling and installation of lateral vents in exposed tank pit.
12-21 December 1987	Extraction vent and 9 pressure-monitoring wells for single-vent test were installed. Two holes sampled to determine vertical contamination distribution. <i>In situ</i> permeability measurements were made at depths from 5 to 30 feet (1.5 to 9.1 meters).
11-17 January 1988	Installed single-vent system at Hill AFB.
18-20 January 1988	Operated single-vent system.
6 June 1988	Drilling and sampling at site. Three holes drilled to 65, 85, and 90 feet (19.8, 25.9, and 27.4 meters.)
July 1988	<i>In situ</i> permeability tests completed. Dry nitrogen injected in 9 pressure-monitoring wells.
August 1988	Drilling for sampling and installation of 14 vertical vents, 25 monitoring vents, and 3 neutron access tubes in area west of tanks. Installed surface barrier in vertical vent area. Soil pile dressed and covered to prevent erosion.
16 September 1988	Water line hit by drilling rig causing flooding of entire soil-venting site. Surface barrier disrupted in 6 foot (1.8 meter) diameter. Repaired surface barrier.
20-23 September 1988	Conducted <i>in situ</i> permeability tests at site.

TABLE 1. CHRONOLOGY OF MAJOR SITE ACTIVITIES (CONCLUDED)

DATE	ACTIVITY
8-11 November 1988	Excavated soil pile was sampled.
18 December 1988 to 9 October 1989	Operation of full-scale system.
12 October 1989	Soil sampling of the pile, water sampling of groundwater monitoring well RST-1, and measurement of <i>in situ</i> soil moisture.
30 October to 6 November 1989	Soil samples taken from vertical vent area for post-venting analysis.
6 November 1989	Drilling for collection of soil samples was completed.

### 3. Report Organization

This report is broken into several main sections describing each of the various phases and tasks covered in this study. Section II describes all methods and materials used in each phase of the demonstration. Section III describes aspects of geological and chemical characterization of the contaminated area under study. Section IV describes the pilot studies used to gather information for full-scale system design and projection of system behavior. Section V details the full-scale *in situ* soil venting system including hydrocarbon removal results from soil venting and bioactivity. Data on costs associated with this technology are presented in Section VI. Section VII contains the conclusions drawn from this study along with recommendations for future work in this area. This is followed by the appendices, including tables of data.

## SECTION II

### METHODOLOGY

#### A. DRILLING

Drilling was conducted for collection of soil samples and installation of vertical vent wells and monitoring points. All borehole locations were marked by staking before drilling. Borehole locations and surface elevations were determined by surveying after installation.

All boreholes sampled throughout the vertically vented zone were augered using an 8-inch [20.3 centimeter (cm)] hollow-stem auger having a 4.25-inch (11 cm) inner stem diameter, operated with a truck-mounted drilling rig. These included the pilot vent and associated monitoring points (31-41), the three deep characterization boreholes (42-44), all vent wells (V1-V15) and monitoring points (A-BB), and post-venting boreholes (V1A-V15A). After core collection, the vent boreholes (V1-V15) were reamed out with a 10-inch (25.4 cm) hollow-stem auger prior to placement of vent pipes.

Neutron access tubes were installed in boreholes dug with a 2-inch (5.1 cm) outside diameter (OD) solid auger bit mounted on the drill rig.

The upper 6 feet (1.8 meters) of vent well boring V15 and post-venting borehole 15A were dug by hand using a bucket auger to minimize the risk of encountering underground piping or electrical lines that were known to be present within 20 feet (6.1 meters) of the boring location at the southeastern corner of the site.

In several boreholes, groundwater was encountered before the completion depth of 50 feet (15.2 meters). In these boreholes drilling was terminated due to concern that sand movement into the borehole may increase the risk of equipment loss. In these situations, the CRNL Grand Junction geologist decided to terminate the borehole, after consultation with the driller.

Borings conducted in the tank excavation and in the excavated soil pile, both before and after venting, were dug using a "Little Beaver" powered auger.

#### B. LOGGING OF BOREHOLES

Soil samples were logged for soil color and texture using standard geological classification systems. All continuous split-barrel and split-spoon samples were logged; in addition, auger cuttings were logged at 5-foot (1.5 meter) intervals from borings which were not sampled.

Cores collected with a split spoon were visually logged using material obtained from the uppermost brass liner. Zones of potential high or low permeability (i.e., gravel or clay) which could affect vapor flow during the venting test, apparent moisture, and presence/absence of petroleum odor were noted. Visible changes in facies were recorded within 0.5 feet (15 cm) vertical resolution.

Hydrocarbon vapors released from all soil samples upon opening of the split-spoon or split-barrel sampler were measured at a distance of 12 inches (30 cm) using an HNu Total VOC Analyzer.

## C. SOIL SAMPLING AND HANDLING

### 1. Excavation Samples

Soil samples were collected during the initial characterization boring in the tank excavation by use of a bucket auger.

### 2. Borehole Sample Collection

In the pilot vent 31, borehole 41, and post-venting samples (V1A, etc.) split-spoon samples were collected exclusively. In the three deep boreholes 42-44, vent boreholes, and monitoring points E and Y, core samples were collected by alternating a split-spoon sampler with a continuous split-barrel sampler.

For borings sampled exclusively with a split spoon, samples were collected at 5-foot (1.5 meter) intervals throughout the borehole (0-1 feet, 5-6 feet, 9-10 feet, etc.). For boreholes sampled with both split-spoon and continuous split-barrel sampler, split-spoon core samples for JP-4 analysis and soil characterization were obtained during augering at 3-foot (0.9 meter) intervals through the upper 15 feet (4.6 meters) of each hole, and at 5-foot (1.5 meter) intervals below that point.

In each vent borehole and sampled monitoring point, the first split-spoon sample was collected when the augered hole was approximately 18 inches (46 cm) beneath ground surface to reduce the likelihood of surface soil contamination from heavy equipment and to avoid sampling the reworked soil covering the surface vapor barrier. Nominal core depth intervals over the upper 15 feet (4.6 meters) of soil were approximately 2 to 3 feet (0.6 to 0.9 meters), 5 to 6 feet (1.5 to 1.8 meters), 8 to 9 feet (2.4 to 2.7 meters), 11 to 12 feet (3.4 to 3.7 meters), and 14 to 15 feet (4.3 to 4.6 meters). Nominal depth intervals of samples collected below the 15-foot (4.6 meter) depth level were approximately 19 to 20 feet (5.8 to 6.1 meters), 24 to 25 feet (7.3 to 7.6 meters), 29 to 30 feet (8.8 to 9.1 meters), 34 to 35 feet (10.4 to 10.7 meters), etc. The depth of each cored interval beneath the excavation surface was determined within 0.5 feet (15 cm).

Split-spoon samples were obtained using 2-inch (5.1-cm) diameter x 6-inch-long (15-cm) brass liners (Environmental Instrumentation, Inc., Concord, CA). The spoon was 18 inches long x 2.5 inches OD [2 inches inside diameter (ID)] to permit use of the liners. Three sleeves were installed in a split spoon for each sample collected.

Continuous split-barrel core samples for visual soil characterization logging were obtained throughout the intervals between split-spoon samples. The continuous split-barrel sampler was 5 feet long.

All downhole equipment was washed with detergent and rinsed with clean tap water before each new borehole was begun.

### 3. Sample Handling

#### a. Bucket Auger Samples

Samples collected by bucket auger during the initial sampling from borings beneath the tank excavation were mixed in a stainless steel pan using a spatula immediately upon retrieval, and were packed into 40-milliliter (mL) vials. These samples were stored in coolers on blue ice, and were shipped immediately to ORNL for analysis. (This method probably allowed volatilization of some organics, as discussed later.)

#### b. Borehole Samples

For the vent well boreholes and pressure monitoring points E and Y, two samples were obtained from each core for JP-4 analysis: one for fuel residue screening, and the other for analysis by a more precise laboratory procedure. The sample for screening consisted of the middle brass liner from the split spoon, while the sample for quantitative JP-4 analysis consisted of the lower brass liner. Upon removal from the split spoon, the ends of each brass liner to be analyzed for fuel residues were immediately sealed with 4-inch (10.1 cm) squares of 3-mil-thick Teflon® film and capped with plastic caps (Environmental Instrumentation, Inc., Concord, CA). The caps were firmly attached to the brass liner tube with electrical tape. Each liner tube was labeled securely and packed in a plastic bag for shipment to ORNL. Each lower liner (designated for precise laboratory hydrocarbon analysis) was handled in an identical manner to the middle (screening sample) liners except that after sealing the ends, the sealed liner was weighed and the gross weight recorded.

Field replicate samples were drawn from the upper brass liner tubes from the split spoons collected in the upper 15 feet (4.6 meters) of soil. One core from each borehole was replicated for the JP-4 screening analysis; a second core from each borehole was replicated for the quantitative analysis. Cores were selected for use as field replicates on the basis of (1) how completely the upper brass liner was filled with soil upon removal from the sampler, and (2) similarity of appearance of the upper and middle liner samples.

Discrete samples were collected from the surface of clay layers observed in the continuous sampler cores during logging by removing a 1-foot length of the core directly above the upper surface of the clay layer immediately upon collection. Each sample was transferred with minimal mixing to a clean glass sample jar, which was filled as full as possible to minimize headspace and sealed with a Teflon®-lined lid.

Samples were collected during post-venting sampling in an identical manner using three sleeve liners in each driven split-spoon sample, but only the lower tube was routinely sealed for subsequent analysis. Approximately 10 percent of middle sleeve liners, selected from depth intervals which contained high pre-venting hydrocarbon levels, were sealed to serve as field replicates.

Before each sampling campaign, two clean brass liner tubes were filled with clean sand in Grand Junction, transported to the work site, opened, and sealed with a Teflon®-lined lid to serve as trip blanks. One tube was included with the soil samples intended for JP-4 screening analysis, and the other, with the samples to be sent to ORNL for quantitative analysis. All sampling equipment was rinsed sequentially with clean tap water and isopropanol (or acetone) between samples.

Immediately after collection, all samples were stored on blue ice, using separate coolers for middle and lower brass liners, and were shipped within 24 hours of collection via overnight air freight to ORNL. In the laboratory, samples were frozen immediately and held at -20°C until analysis. Chain-of-custody procedures were employed throughout sample handling and analysis.

### c. Pile Samples

Samples were collected from the excavated soil pile in 12-inch-long (30-cm), 0.75-inch-diameter (1.9-cm) stainless steel tube liners. Each sample tube was driven into the soil after removal of the auger at the designated depth and withdrawn using a steel rod attached to the tube holder. Tubes were sealed, identified, stored, and shipped identically to the brass split-spoon liners.

## D. SOIL CHARACTERIZATION

### 1. Moisture Content

Moisture content was determined on each soil sample returned to ORNL for hydrocarbon analysis. An 80-gram sample was removed from the brass sleeve liner using a cork borer, was transferred to a clean, tared 8-ounce (237 mL) flint glass jar, and was dried to constant weight (48 hours) at 105°C in a forced-air oven (Reference 8). Moisture content was expressed on a dry-weight basis:

$$\theta_w = \frac{(\text{weight of wet soil} + \text{tare}) - (\text{weight of dry soil} + \text{tare})}{(\text{weight of dry soil} + \text{tare}) - \text{tare}} \quad [1]$$

### 2. Bulk Density

Cores collected in brass split-spoon sleeve liners from boreholes 31 and 41 were trimmed to lengths of 4 to 6 inches (10.2 to 15.2 cm) immediately upon collection; the length and weight of each was then determined. The core material was then transferred to tared metal drying tins, which were transported back to the laboratory, where the dry weight of the soil was determined. The dry bulk density was calculated as: (dry soil mass)/(core volume) after Reference 8.

### 3. Particle Size Analysis

The particle size distribution of selected soil samples was determined according to ASTM procedure D422-63 (ASTM 1985). Samples were prescreened through a dry No. 10 sieve to remove gravel, followed by hydrometer determination of sand [2 mm to 50 micrometers ( $\mu\text{m}$ )], silt (50  $\mu\text{m}$  to 2  $\mu\text{m}$ ), and clay (less than 2  $\mu\text{m}$ ) particle size ranges. Results were reported as a mass fraction of the total sample.

## E. NEUTRON ACCESS TUBES

Neutron scattering is an efficient and reliable technique for monitoring soil moisture. The technique is based on the capacity of hydrogen to absorb efficiently the energy of "fast" neutrons through collisions, and to reduce their energy to the "thermal" neutron range. In practice, a probe containing both a source of "fast" neutrons and a detector of "thermal" neutrons is lowered into the ground through an access tube. The energy contained in "fast" neutrons radiated into the soil from the source (generally an alpha particle-emitting radioisotope mixed with beryllium) is absorbed by the hydrogen contained in water or organic materials in the vicinity of the probe, and a steady-state field of "thermal" neutron field, which is nearly proportional to the density of hydrogen in the vicinity (10-25 cm radius) of the probe, is then measured. Because the intensity of the "thermal" neutron field varies with soil type, measurements are most precise when the instrument is calibrated in the particular soil to be monitored (Reference 9).

### 1. Installation

Holes for the three neutron access tubes were bored as described above (Section II.A.). Each was bored to a depth of 54 feet (16.5 meters) BLS to accommodate installation of the tube to a depth of 50 feet (15.2 meters).

The initial borehole for one of the neutron access tubes (NA2) encountered a gravel lens in the upper 10 feet (3 meters), causing collapse of the borehole, and had to be abandoned after backfilling with native soil. Tube NA2 was bored, sampled, and installed successfully about 6 feet away.

The initial borehole for NA1 encountered similar problems and was abandoned. A second borehole was successfully dug and sampled to a depth of 35 feet (10.7 meters) at which point a mud lens was encountered and collection of the final sample was not possible. A third boring was dug within 2 feet (0.6 meters) and the tube was installed without sampling.

Soil samples were collected during drilling with 2-inch-diameter (5.08-cm), 36-inch-long (0.91-meter) Shelby tubes after augering to a point approximately 6 inches (15.2 cm) above the desired sampling depth. Samples were collected at nominal depths of 3, 20, 35, and 45 feet (0.94, 6.1, 10.7, and 13.7 meters) BLS. Following removal from the Shelby tube, each soil sample was weighed and placed in a tared soil tin, sealed, and returned to the laboratory for determination of moisture content.

### 2. Calibration

Immediately after setting of tubes, each neutron access tube was logged using a Troxler Model 3330 Neutron Logger to permit calibration of the instrument against the moisture contents of the soil samples collected during installation. The instrument slope and zero controls were adjusted to 1 and 0, respectively, in accordance with the instrument operating manual. Readings consisted of 30-second counts at depth intervals of 1 foot (0.30 meters) throughout the tubes to a final depth of 45 feet (13.7 meters).

The moisture contents of soil samples collected during installation were determined according to the procedure outlined in Section II.D.1. Instrument readings were calibrated to field moisture



content by linear regression. The regressed relationship, which was used for the three tubes throughout the study, was determined to be

$$\text{Moisture content (kg/m}^3\text{)} = 0.77 (\text{Troxler reading}) - 14.66.$$

[2]

Soil moisture logs were determined before the operations and every other month during the venting operation, with the exception of the month of April 1989. During the periods between logging, the Troxler instrument was stored in a locked cabinet in the analytical trailer to prevent inadvertent exposure to the neutron source.

Soil sampling and handling procedures, logging procedures, and calibration data are included in unpublished Appendix J, available from ORNL and AFESC (see Preface for instructions.)

## F. SOIL CHEMICAL ANALYSIS

### 1. Petroleum Hydrocarbon Screening

#### a. Infrared Analysis

A set of 46 field replicate soil samples collected from boreholes 42-44 were screened for total hydrocarbon content by a contract laboratory using freon extraction followed by infrared quantitation, in accordance with USEPA Procedure 503E. Correlation of the analyses with laboratory analyses performed on the replicate pairs, however, was very low. Results were generally near the detection limit (4 mg/kg total hydrocarbons), even for samples which were observed to emanate strong petroleum odors and samples for which field replicates contained high levels of hydrocarbons. Because of the apparent potential for false negative results, use of this method for screening of additional samples was discontinued.

#### b. Gas Chromatographic Analysis

An alternate screening method utilizing headspace gas chromatography was developed, tested, verified, and applied to screening of samples from the vent well and pressure monitoring point installation boreholes. Replicate soil sample in sleeve liners were thawed, and approximately 20-gram portions were transferred with a cork borer to 40-mL VOC vials and sealed with Teflon® septa.

After equilibration for 30 minutes, a 250-microliter ( $\mu\text{L}$ ) aliquot of headspace gas from each vial was analyzed for total hydrocarbons in a Perkin Elmer Model 3920 gas chromatograph equipped with a flame ionization detector (FID) and a 2-foot x 1/4-inch (0.61-meter x 0.64-cm) glass column packed with 4 percent OV-101. Injector and oven temperatures were 150°C and 130°C, respectively; the nitrogen carrier gas flow rate was 40 mL/minute. The instrument was calibrated with headspace vapor equilibrated with kerosene in a VOC vial. Analytical results were expressed as the direct output of the integrator (Hewlett-Packard Model 3390), measured in microvolt-seconds.

To calibrate the method, a set of 42 replicate soil samples from the vent well installation borings, whose replicate pair had already been analyzed using the more extensive laboratory

procedure, were analyzed using the gas chromatographic screening procedure. The logarithmic transformations of the screening and analytical data were highly correlated:

$$\log C \text{ (in mg/kg)} = 1.51 \log (\text{Plot area}) + 0.82 \quad (R^2 = 0.79).$$

[3]

More significantly, no samples containing detectable (greater than 20 mg/kg) hydrocarbons produced a headspace response of less than  $4.5 \times 10^5$  integrator units. This value was thus selected as the response criterion for subsequent laboratory analysis of the paired replicate sample.

A total of 12 of the 42 samples analyzed the calibration test produced screening responses of greater than  $4.5 \times 10^5$  integrator units, with no hydrocarbons (less than 20 mg/kg) detected in the paired sample analyses. The screening method therefore was concluded likely to result in some false positive identifications of samples for subsequent laboratory analysis. Because this was deemed far less objectionable than false negatives (i. e., samples falsely identified as containing undetectable hydrocarbons), the method was employed in screening of the remaining 70 samples from the vent/monitoring well installation borings. Of these, a total of 14 were identified for subsequent laboratory analysis of the paired replicate.

## 2. Laboratory Hydrocarbon Analysis

The total concentration of petroleum hydrocarbons in soil samples was determined by the ORNL Analytical Chemistry Division (ACD) by solvent extraction of the sample followed by capillary column gas chromatography with flame ionization detection, according to ACD Master Manual Method No. 1221029, Revision 2, 15 July 1988 (included in Appendix J, unpublished, available from ORNL and AFESC). Following the initial round of sample analyses (the tank excavation samples), the method was modified by use of a larger soil-mass-to-solvent volume ratio (20 grams soil:10 mL mixed solvent) during the extraction step to lower the detection limit to 20 mg/kg. Total hydrocarbon concentration was reported on an as-received (i.e., wet weight) basis.

Pristane was used as internal standard. A mean response factor was determined for the entire suite of hydrocarbons separated on the chromatogram by use of authentic JP-4 standards, which were run at least twice per analytical run (approximately 40 samples). Recovery of JP-4 sample "spikes" was determined at least once per analytical run. The mean JP-4 recovery for 28 spikes was 107 percent [standard error (SE) = 6 percent]. Two standards were run per analytical run.

Paraffins (i. e., n-alkanes) were identified in chromatograms of soil samples by comparison with an n-alkane standard mixture, consisting of  $C_6$  to  $C_{17}$  compounds. Individual compounds were quantified for selected samples using compound-specific response factors.

Boiling ranges were defined by paraffins; each paraffin defined the high-boiling (i. e., latest-eluting) component within a boiling range, which was labeled according to the paraffin (e. g., n-decane defined the high-boiling end of the  $C_{10}$  range). Gas chromatographic-mass spectrometric analysis of selected sample extracts was used to confirm identifications of compounds within each boiling range.

### 3. Benzene/Toluene/Xylene (BTX)

Selected soil extracts were analyzed for benzene, toluene, and xylene (BTX) by the standard petroleum hydrocarbon quantitation procedure described above, but using a wide-bore capillary column and modified chromatograph temperatures to increase resolution of the low-boiling components.

## G. GROUNDWATER ANALYSIS

### 1. Sampling and Handling

Water samples were collected from the on-site monitoring well (RST-1) at the conclusion of the vertical venting campaign to determine whether venting had affected groundwater quality. Water samples were collected using a Teflon® bailer following purging of 3 bailer volumes from the well. Replicate samples were collected in 1-liter glass bottles for semivolatile organics (SVO) analysis, and in 40-mL VOC vials for volatiles analysis. Sample containers were immediately placed on blue ice in a cooler, which was shipped to ORNL via overnight air freight.

### 2. Analysis

Volatile organics analyses (VOA) were determined by gas chromatography according to USEPA Method No. 8240 (Reference 10).

SVO were extracted from the water samples using USEPA Method No. 3510, and were analyzed by capillary gas chromatography using USEPA Method No. 8270 (Reference 10).

## H. GAS FLOW RATES

The flow rate of the gas moving through the pipes of the ISSV system was determined by measuring the velocity of the gas. Velocity measurements were converted to flow rates by multiplying the velocity by the cross-sectional area of the pipe. Velocity measuring devices which were used include (1) orifice plates, (2) rotameters, and (3) velocity meters. The flow rates were converted to standard flow rates using an assumed constant barometric pressure of 640 mm Hg (85,300 Pascals), corresponding to the altitude of the site.

### 1. Orifice Plates

Orifice plates were used in several points in the soil venting system: (1) the vertical vent manifold system, (2) the pile manifold system, (3) the lateral vent manifold system, and (4) the discharge of the blowers. They were also used to measure the discharge in the pilot vent test. Orifice plates create a pressure drop which can be easily measured by magnehelic gauges or U-tube manometers. The pressure drop is used to calculate velocity in the pipe, and thus flow rate, based on the size of the pipe.

#### a. Calculations for Flow Rate

The following formula (Reference 11) was used to calculate the velocity of the gas through the pipes.

$$V_i = C_o \sqrt{\frac{2g_c \left( \frac{\Delta P}{\rho} \right)}{\left( \frac{S_i^2}{S_o^2} \right) - 1}} \quad [4]$$

where  $V_i$  = average velocity of inlet gas, (L/t)  
 $C_o$  = discharge coefficient (dimensionless), 0.61 for Reynolds numbers greater than 30,000 in the orifice  
 $g_c$  = gravity correction factor for American engineering units (32.2 pounds-mass feet per pound-force seconds<sup>2</sup>)  
 $\Delta P$  = pressure drop across orifice (M/Lt<sup>2</sup>)  
 $\rho$  = density of gas (M/L<sup>3</sup>)  
 $S_i$  = pipe cross-sectional area (L<sup>2</sup>)  
 $S_o$  = orifice cross-sectional area (L<sup>2</sup>)

The maximum  $\Delta P$  was only 10 inches of water (2500 Pascals), so this equation for incompressible flow is satisfactory. The flow rate of gas in the pipe was calculated from the velocity by the following equation.

$$Q = S_i \cdot V_i \quad [5]$$

where  $Q$  = volumetric flow rate of gas in the pipe (L<sup>3</sup>/t)

#### b. Standard Flow Rate

The flow rate was converted to standard conditions by the following equation. Flow rate correction due to temperature difference was considered to be negligible.

$$Q_s = Q \cdot P/P_s \quad [6]$$

where  $Q_s$  = Standard flow rate of gas in the pipe (L<sup>3</sup>/t)  
 $P$  = Absolute Pressure at point of measurement (M/Lt<sup>2</sup>)  
 $P_s$  = Standard Pressure (M/Lt<sup>2</sup>)

## 2. Rotameter

During the early operation of the full-scale system, a rotameter was initially used to measure the flow rate when the extraction rates were low. The rotameter's full-scale range was 0 to 60 standard cubic feet per minute (scfm) [1.70 standard cubic meters per minute (scmm)]. After extraction rates increased above 60 scfm, orifice plates were used for measurement of flow rate.

### 3. Velocity Meters

Velocity meters were used primarily for determination of relative flow rates from operating vents. Two types of velocity meters were used: a velometer and a hot-wire anemometer. These meters were typically used at the head of the extraction vents. The maximum velocity was recorded and converted to an average velocity by multiplying the maximum velocity by 0.8. This method, which was obtained from Reference 11, is valid for conditions of turbulent flow. The flow rate was calculated using equations [5] and [6].

#### a. Velometer

An Alnor Model 6000AP velometer was used during the first 24 hours of full-scale operation, then a switch was made to the rotameter described above. It was later used to determine the velocity of the gas stream from the individual vents. The velocity was measured by inserting the velometer probe into the pipe perpendicular to the gas flow and reading the velocity directly off the scale.

#### b. Hot-Wire Anemometer

The gas that was initially extracted from the vents was high enough in hydrocarbon concentration to be above the lower explosive limit (LEL). The hot-wire anemometer was not used until the extraction gas from the vents had decreased to a concentration below the LEL since there was some concern about inserting the hot-wire anemometer into an explosive gas stream. The concern was due to the possibility of the filament breaking and causing a spark which could initiate an explosion, rather than the temperature of the wire.

## I. GAS ANALYSES

Gas samples were collected on a regular basis to monitor the progress of the ISSV demonstration. Analyses performed on the gas samples included:

- Hydrocarbons by Gas Chromatography (GC) Analysis
- Hydrocarbons by Continuous Analysis
- Explosive Gas by Continuous Analysis
- Carbon Dioxide
- Oxygen
- Humidity

### 1. Hydrocarbons by GC Analysis

#### a. Collection

Gas samples taken for GC analysis were collected by three methods: (1) Traps, (2) Canisters, and (3) Tedlar® Bags.

(1) **Traps.** Supelco™ Carbotrap™ 300 tubes were used to trap hydrocarbon samples during the single-vent pilot test. The traps were connected to the system by a 1/4-inch (0.635-cm) valved tee downstream of the sampling line feeding the total hydrocarbon analyzer (THA). Results from the one-vent test indicated that the gas stream was too concentrated to obtain accurate and reproducible results with sampling traps. It is possible that the traps could be used near the end of the ISSV process when the VOC concentration is much more dilute.

(2) **Canisters.** Brass canisters, which had been evacuated to approximately 25 inches Hg (84,700 Pascals) vacuum, were used to obtain samples throughout the full-scale test. Samples were taken from the extraction vents through heat-traced valves. Special probes were attached to the canisters to obtain gas samples from the oxidizers' stacks.

(3) **Tedlar® Bags.** During the first month of operation of the full-scale system, the individual extraction vents were sampled from the heat-traced sampling port with a small portable gas sampling pump in addition to sampling with the brass canister. These samples were collected in Tedlar® bags. Due to losses and analysis variabilities, these data were not used. However, the results were kept on record as listed in unpublished Appendix J (available from ORNL and AFESC).

#### **b. Analysis**

All three types of samples were analyzed for hydrocarbons by the Utah Water Research Laboratory (UWRL) of the Utah State University (USU). The data were presented as mass of equivalent compound recovered and the corresponding vapor concentrations. Concentration data were provided in units of weight of equivalent standard compound per volume of air and included the following:

- (1) Mass and concentrations of C-5 to C-17 n-paraffins using individual retention time and response factors for each paraffin of interest in quantitative calibration mixtures.
- (2) Mass and concentrations of compounds representing boiling ranges defined by the C-5 to C-17 n-paraffins using cumulative integrated areas between n-paraffin peaks.
- (3) Mass and concentration of total hydrocarbons using a mean response factor over the C-5 to C-17 n-paraffin range.
- (4) Mass and concentrations of specific aromatic compounds (benzene, toluene, ethylbenzene, xylenes) using individual retention time and response factors for each compound of interest in quantitative calibration mixtures.

After analysis, the sampling canisters were purged with nitrogen to remove all traces of hydrocarbons and evacuated for reuse.

## **2. Hydrocarbons by Continuous Analysis**

### **a. Equipment**

A Beckman Industrial Model 400A THA was housed in the analytical trailer and used for continuous determination of hydrocarbon levels in the system. As implied by the name, this

instrument measures the quantity of all of the hydrocarbon compounds in the gas stream. The analyzer uses a FID.

#### **b. Calibration**

Since the FID responds to all hydrocarbon compounds, the instrument is calibrated with a particular hydrocarbon gas and the results are expressed in terms of the calibration gas. For example, during the full-scale demonstration hexane was used to calibrate the instrument, and the results are reported as ppmv hexane equivalent. Ambient air was used to set the zero level of hydrocarbons in air. The THA was calibrated daily using certified hexane standard gases (500 and 5000 ppm or 2590 ppm). The concentrations of hydrocarbons (as hexane equivalent) were easily determined since the THA responds linearly in the range it was operated.

#### **c. Concentration Measurement**

A sidestream (approximately 3 liters/minute) was acquired from the desired sampling point by a gas sampling pump and transferred to the THA through insulated, heat-traced 1/4-inch stainless steel or copper lines to keep the gas from condensing in the sampling lines. The THA uses only a small portion of the sidestream, and the unused portion was returned to the system for treatment by the catalytic oxidation system. The THA oxidizes the hydrocarbon components in the sample completely, and the analyzer's exhaust is vented to the atmosphere.

The THA has been shown to exhibit non-linear behavior above its full-scale range. However, since the feed to the catalytic oxidation system could not exceed 25 percent LEL (0.325 percent by volume), manual dilution of the gas to stay below the 25 percent LEL limit maintained the hydrocarbon levels below the THA's full-scale range during the full-scale demonstration. The THA was operated continuously during the operation of the system.

### **3. Explosive Gas Monitor**

#### **a. Equipment**

A Mine Safety Appliances (MSA) Model 510 combustible gas monitor was used to monitor the concentration of hydrocarbon levels, in terms of the LEL, at four locations: (1) extraction gas (discharge side of blower), (2) extraction gas (knock-out drum), (3) near the ceiling in the analytical trailer, and (4) near the floor of the analytical trailer. The monitoring head for the knock-out drum always displayed a much lower concentration than the monitoring head on the discharge side of the blower. It is believed that the head may have been affected by the vacuum applied on the knock-out drum, or there may have been small leaks at the connection, allowing entrance of atmospheric air.

#### **b. Calibration**

Initially, the monitoring heads were calibrated once per week with pentane (29 percent LEL). As the process continued, it was apparent that it was not necessary to calibrate the heads as often. Thereafter each monitoring head was calibrated with pentane at least once per month as specified by the manufacturer.

### c. Action Upon Positive Readings

The MSA displayed the concentration in percent LEL. When the oxidation unit and blower were operated at the same flow rate, the MSA was set up to activate a caution alarm when the level was between 10 and 20 percent of LEL, and to automatically shut the blowers down if the concentration exceeded 20 percent. During the startup phase of operation, the oxidizer pulled in ambient air through a dilution tee diluting the concentration by two; therefore, the concentration of the gas from the vents was maintained at twice the normal operating level during this period, and the shutdown limits for the circuits measuring the extracted gas were doubled.

### 4. Carbon Dioxide

Gas samples were obtained from the extraction vents for carbon dioxide ( $\text{CO}_2$ ) analysis to monitor the products of bioactivity. Gas samples were taken from the vents with a small portable gas-sampling pump and collected in Tedlar® bags. The concentration of  $\text{CO}_2$  was determined on-site in the analytical trailer. The concentration of  $\text{CO}_2$  was determined by Sensidyne Gastec analyzer tubes which were rated in the ranges 300 to 5000 ppm, 0.13 to 6 percent, 0.5 to 20 percent, and 2.5 to 40 percent  $\text{CO}_2$ . These tubes were listed to have an accuracy of 25 percent. A Bacharach FYRITE® instrument was also used to measure the concentration of  $\text{CO}_2$  in the gas sample.

### 5. Oxygen

Gas samples for the determination of the concentration of oxygen ( $\text{O}_2$ ) were collected at the same time as the  $\text{CO}_2$  samples and in the same manner. These samples were also analyzed on-site in the analytical trailer. The concentration of  $\text{O}_2$  was determined with a portable Universal Enterprises Model C5 electronic oxygen analyzer, which had a range of 0 to 25 percent. A Bacharach FYRITE® instrument was also used to determine the oxygen concentration of the gas samples.

### 6. Humidity

Humidity in the extracted soil gas was monitored to determine the effect of venting on soil moisture and the system performance. Humidity was measured at each vent head and the extraction manifold. The measurements were made with a General Eastern 800B portable combination humidity temperature probe which operates using a bulk polymer capacitance measurement.



## SECTION III

### SITE CHARACTERIZATION

During the Hill AFB soil venting study 113 boreholes were drilled to provide characterization data about the geohydrology and petroleum hydrocarbon contaminant distribution within the venting area. Many of these boreholes were then used in installation of vent and pressure monitoring wells immediately following logging and sample collection.

A summary of the borings drilled at the spill site is found in Table 2. All of the boreholes installed at the site are shown in Figure 5. Pile samples are shown separately in Figure 12.

The boreholes installed beneath the excavation (1-30) were logged by observation of the samples obtained by hand-augering at intervals. Borings installed during the pilot well installation (31-41), the borings installed for investigating potential for migration at depth and to the east (42-44), and borings associated with vent and pressure monitoring installations (V1-V15, A-BB) were logged by inspection of continuous core as well as detailed examination of samples obtained at regular intervals with a lined split spoon. Pile samples (P1-P12) were logged by examination of cores collected at pre-defined intervals. Borings drilled for installation of neutron access tubes and for post-venting sample collection were not logged.

#### A. GEOHYDROLOGY

##### 1. Stratigraphy

From examination of the borehole logs the fuel spill site is characterized in general as consisting of unconsolidated to weakly consolidated sand, with thin lenses of clay. The sand is generally described as light yellowish brown to pale brown, very fine to fine grained, and poorly sorted. Gravel and pebbles were reported at irregular intervals in some boreholes, but without continuity between boreholes. Geologic logs of all borings in the spill area are found in Appendix J (unpublished, available from ORNL and AFESC).

East-west cross-sections across the northern and central portions of the site are shown in Figure 6. A third east-west section across the southern portion is shown in Figure 7. North-south cross-sections are shown in Figures 7 and 8. The cross-sections show the presence of numerous clay lenses throughout the upper 40 feet (12.2 meters) of sand. Most of the clay lenses are 6 to 12 inches (15 to 30 cm) thick, and extend between no more than one or two adjacent boreholes in most cases.

The most significant stratigraphic feature at the site is a thick clay layer encountered at a depth of 24 to 26 feet (7.3 to 7.9 meters) BLS beneath the tank excavation, which appears to be continuous throughout the eastern half of the vertically vented portion of the site, appearing at depths of 36 to 42 feet (11 to 13 meters) BLS [approximately 4715 feet (1437 meters) above mean sea level (MSL)] in borings V10 and V11. The clay layer appears to be 10 to 15 feet (3.0 to 4.6 meters) thick across the southeastern portion of the site, and decreases to 3 to 6 feet (0.9 to 1.8 meters) in the northern boreholes, dipping slightly from east to west. The clay layer was described as ranging in color from reddish yellow in the east to brown in the west, occasionally sandy or silty,

TABLE 2. SUMMARY OF BOREHOLES INSTALLED AT HILL AIR FORCE BASE  
BUILDING 914 FUEL SPILL SITE.

BOREHOLE IDENTIFICATION	NUMBER OF BOREHOLES	DATE OF DRILLING	DRILLING METHOD <sup>a</sup>	PURPOSE <sup>b</sup>	LOCATION
1-30	30	11/87	BA	C/P	Tank excavation
31-41	11	12/87	SS	C/V/P	Vertical vent
42-44	3	6/88	SS	C	Vertical vent
V1-V15	14	8-9/88	CC/SS	C/V	Vertical vent
A-BB	22	8-9/88	CC/SS	C/P	Vertical vent
P1-P12	12	9/88	A/C	C	Pile
V2A-EA	15	10/89	SS	PC	Vertical vent
P1A-P6A	6	10/89	A/C	PC	Pile

<sup>a</sup>BA = Hand-operated bucket auger; SS = Split-spoon sampling through hollow-stem auger; CC = Continuous core sampler;  
A/C = Powered auger with hand-driven core collection from bottom of auger hole.

<sup>b</sup>C = Characterization sampling (pre-venting); V = Vent well installation; P = Pressure monitoring point installation; PC  
= Post-venting characterization.

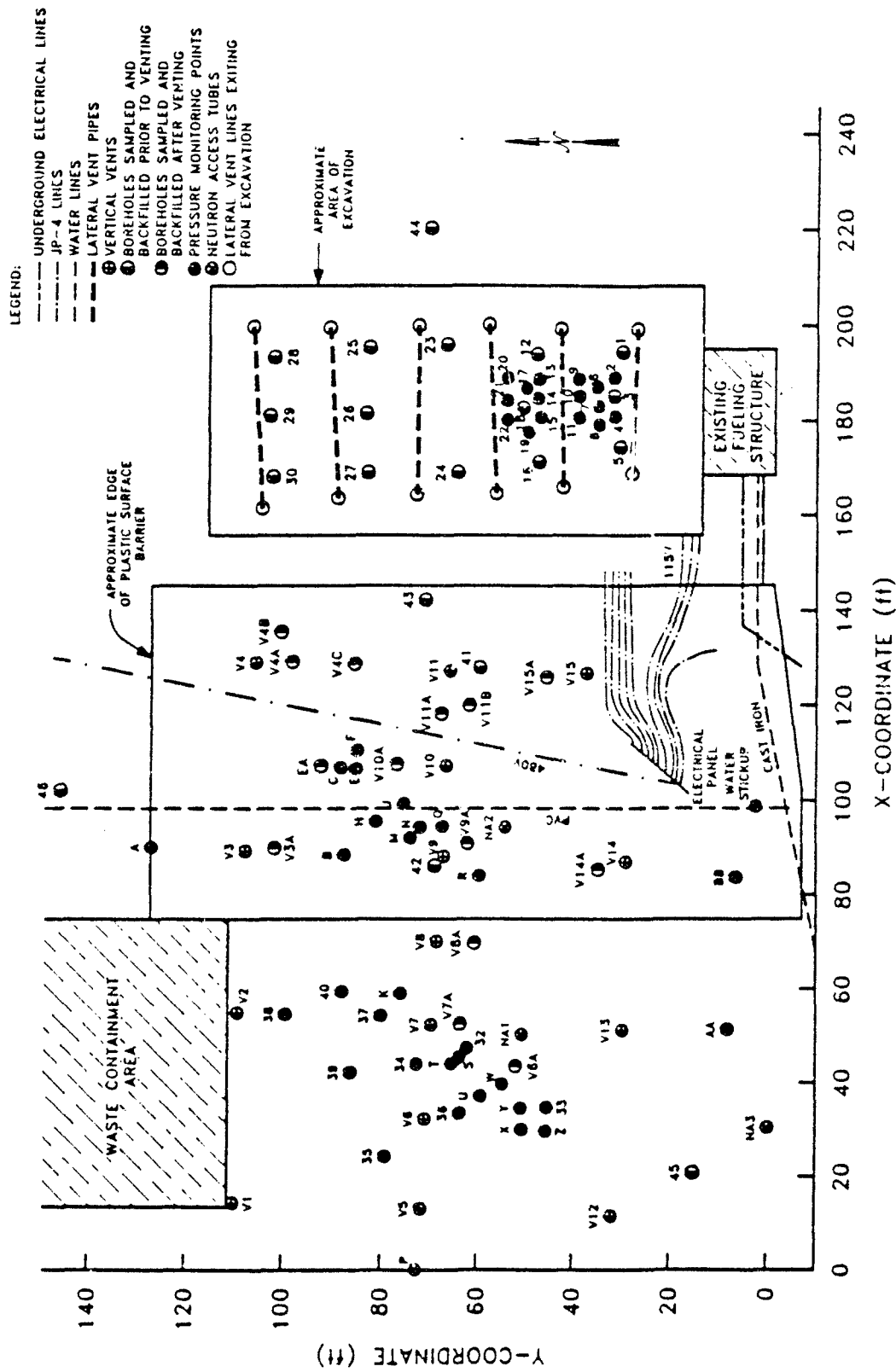


Figure 5. Locations of All Borings Drilled at the Hill AFB Building 914 Fuel Spill Site During the Soil Venting Demonstration from November 1987 through October 1989. Coordinates (feet) Shown are the Project Grid, Established Arbitrarily for Project Use.

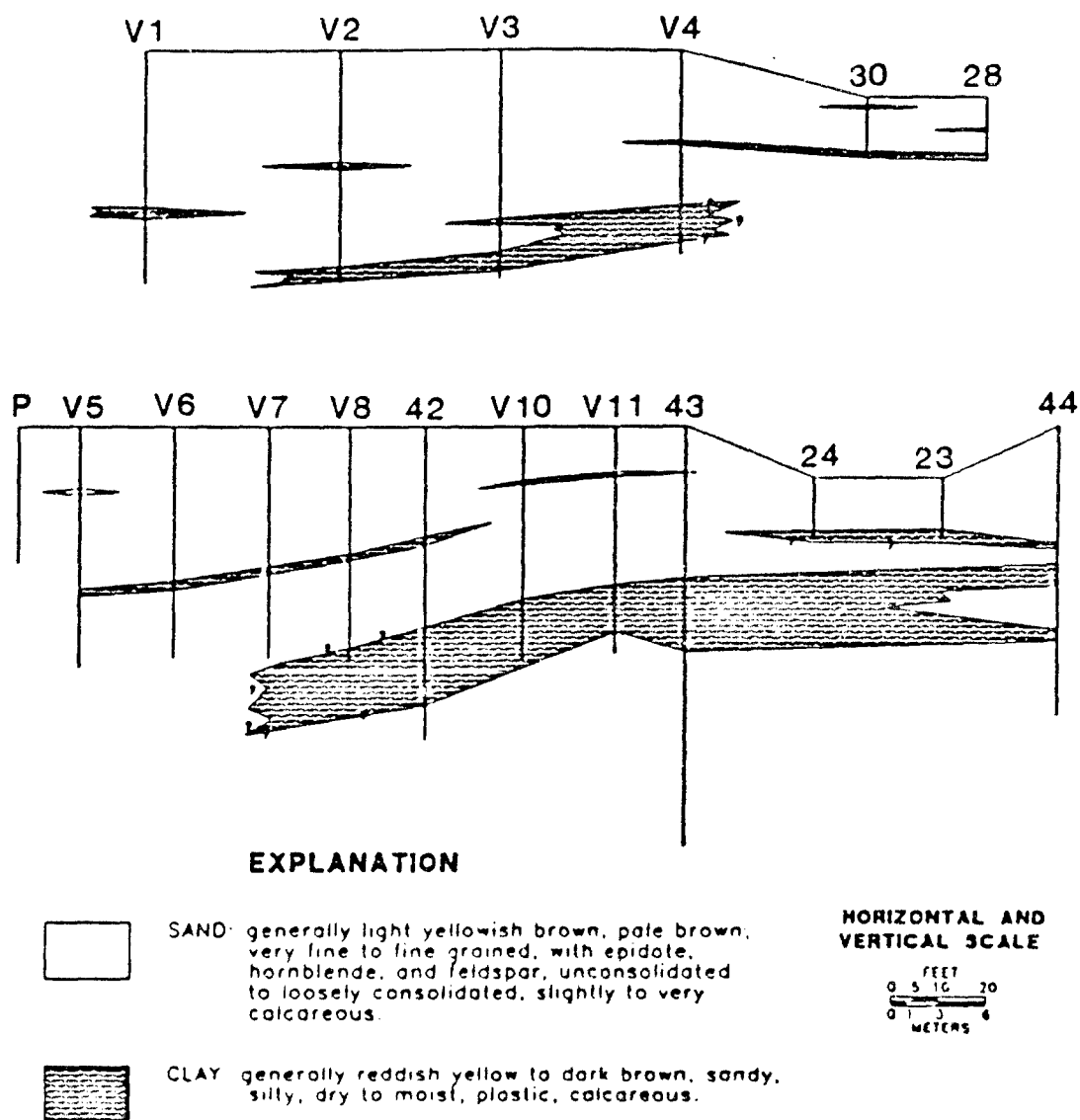
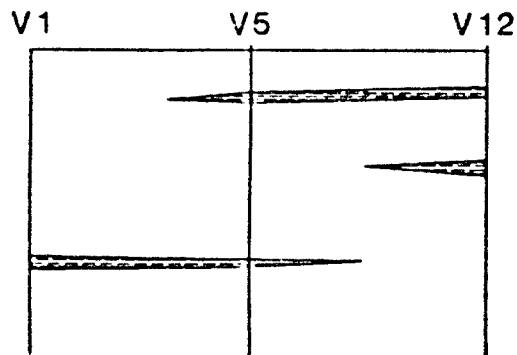
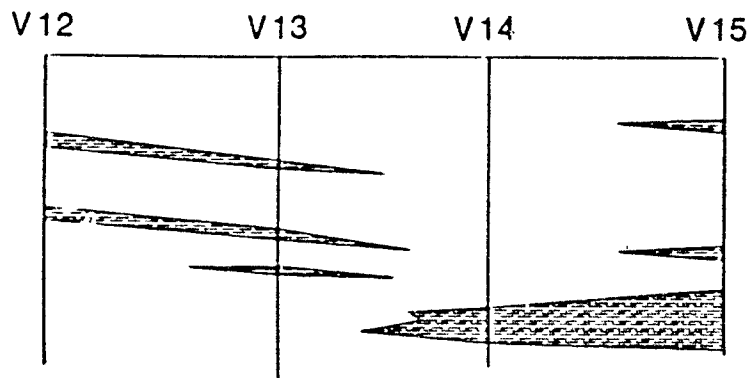


Figure 6. Geologic East-West Cross-Sections Across the Northern and Central Portions of the Spill Site, Based on Logs from Borings Drilled During the Soil Venting Demonstration Project.



### EXPLANATION



**SAND:** generally light yellowish brown, pale brown, very fine to fine grained, with epidote, hornblende, and feldspar, unconsolidated to loosely consolidated, slightly to very calcareous.

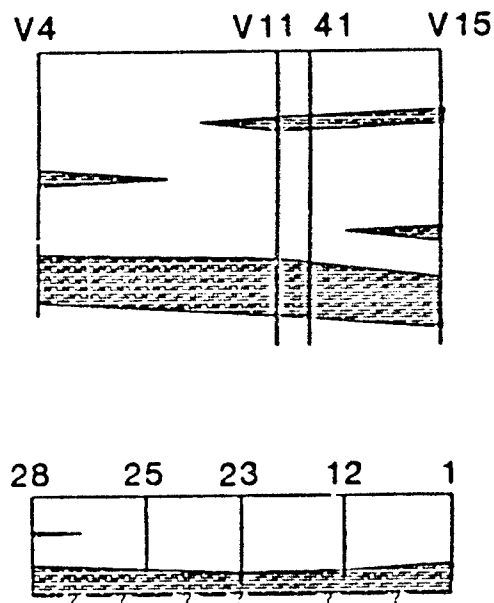


**CLAY:** generally reddish yellow to dark brown, sandy, silty, dry to moist, plastic, calcareous.

### HORIZONTAL AND VERTICAL SCALE



Figure 7. Geologic East-West Cross-Section across the Southern Portion of the Spill site, and North-South Cross-Section Across the Western End of the Site.



### EXPLANATION



**SAND:** generally light yellowish brown, pale brown, very fine to fine grained, with epidote, hornblende, and feldspar, unconsolidated to loosely consolidated, slightly to very calcareous.



**CLAY:** generally reddish yellow to dark brown, sandy, silty, dry to moist, plastic, calcareous.

### HORIZONTAL AND VERTICAL SCALE



Figure 8. Geologic North-South Cross-Sections Across the Center and Eastern End of the Spill Site.

and calcareous, and was generally described as damp to wet, whereas the discontinuous lenses above were described variously as damp to dry. The deep clay layer is seen more clearly in a fence diagram of the site (Figure 9). Because of its thickness and likely near-saturation (Section III.A.3) this underlying clay layer was expected to serve effectively as a lower boundary to vapor flow throughout the eastern portion of the site.

## 2. Soil Characteristics

To evaluate soil particle sizes, 14 samples collected from beneath the tank excavation and 22 samples from borings 31 and 41 in the vertical vent area were analyzed. Results are shown in Table 1 of Appendix A. Samples from depths logged as "sand" during boring contained in all cases more than 90 percent sand and gravel. Samples identified as "clay" during logging [i. e., samples at depths of 24 feet (7.3 meters) BLS or greater beneath the tank excavation, and below 35 feet (10.7 meters) BLS in boring 41] contained 22.5 to 40 percent clay-size particles, with the exception of a sample from boring 31, 25 feet (7.6 meters) BLS, which contained only 6.9 percent clay. The boring 41, 10 feet (3.0 meter) BLS sample is a clay lens identified during drilling. The sample from boring 24, 10 feet (3.0 meter) depth represents a transitional zone from sand to clay (12.1 percent clay). "Clay" samples from beneath the tank excavation and lenses in borings 31 and 41 contained 17 to 30 percent gravel and sand; samples from the continuous bed encountered at a depth of 35 feet (10.7 meters) BLS in boring 41, in contrast, contained only 7 to 11 percent sand and no gravel.

Dry bulk density was determined for the 22 samples from borings 31 and 41 using:

$$\text{bulk density} = \left( \frac{\text{core weight}}{\text{core volume}} \right) \left( \frac{100}{100 + \text{moisture percent}} \right) \quad [7]$$

A range of values from 1.44 to 1.99 grams/cm<sup>3</sup> was determined. Mean bulk densities were 1.67 [Standard Error (SE) = 0.06] grams/cm<sup>3</sup> for 17 "sand" samples and 1.65 grams/cm<sup>3</sup> (SE = 0.03) for 5 "clay" samples. Based on these values and the sample moisture contents, the mean porosities of "sand" and "clay" samples were 0.37 (SE = 0.06) and 0.38 (SE = 0.03) as determined by

$$\text{porosity} = 1.0 - \left( \frac{\text{bulk density}}{2.65} \right) \quad [8]$$

Mean air-filled porosities were 0.35 (SE = 0.05) and 0.04 (SE = 0.04) as determined by

$$\text{air-filled porosity} = \text{porosity} - (\text{bulk density}) \left( \frac{\text{moisture percent}}{100} \right) \quad [9]$$

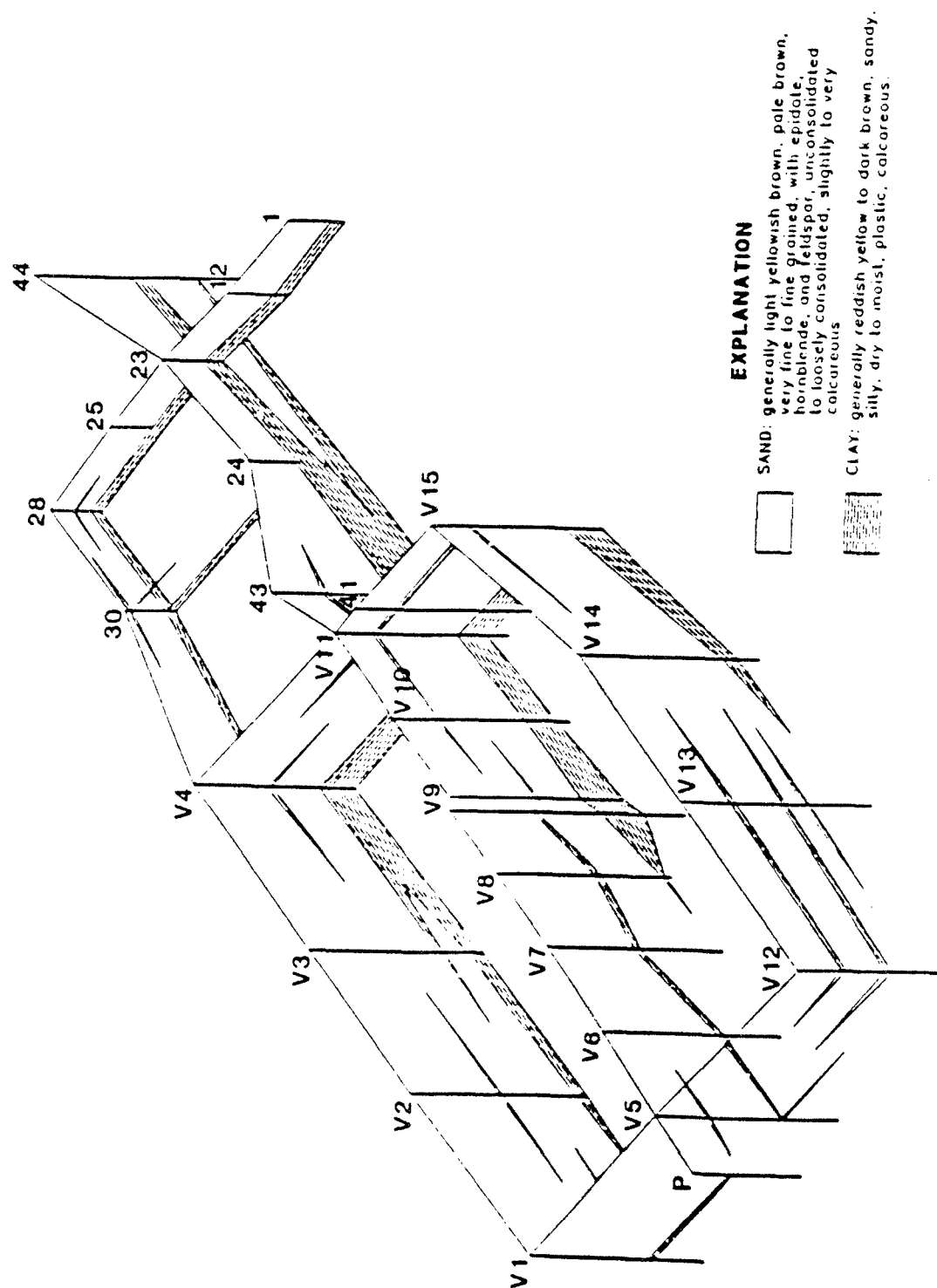


Figure 9. Fence Diagram of Stratigraphic Features at the Building 914 Fuel Spill Site, Based on Geologic Cross-Sections (Figures 6-8).



The low value for clay reflects the high moisture content of the clay samples from these borings, which was generally true throughout the site (Section III.A.3).

### 3. Moisture

#### a. Soil Sample Analyses

Throughout all the spill site, the moisture of sand samples throughout the upper 40 feet (12.2 meters) BLS [and to a depth of 24 feet (7.3 meters) BLS beneath the tank excavation] was generally 3 to 7 percent. The same range occurred in the pile. Higher values (10 to 25 percent) in the sand were generally associated with interfaces with clay lenses.

Samples collected at the surface of and within the underlying clay layer from boreholes V2, V3, V4, V9, and V10 at depths of greater than approximately 40 feet (12.2 meters) generally had moisture contents of 23 to 30 percent, suggesting near-saturated conditions at the clay layer. Water was encountered in boreholes J [47 feet (14.3 meters) BLS] and Y [60 feet (18.3 meters)] during installation. In addition, the following boreholes caved in at depth during installation, indicating saturated conditions: V5 [52 feet (15.8 meters) BLS], V6 [53 feet (16.2 meters)], V8 [49 feet (14.9 meters)], V11 [50 feet (15.2 meters)], V13 [53 feet (16.2 meters)], V14 [53 feet (16.2 meters)], and N [48 feet (14.6 meters)]. Boring 16 beneath the excavated tanks also caved at a depth of 31 feet (9.4 meters) BLS. These results are indicative of saturated conditions across much of the spill site at a depth of approximately 45 to 55 feet (13.7 to 16.8 meters), corresponding to water levels recorded in monitoring well RST-1 prior to the venting period.

Moisture content of 11 pairs of replicate samples from the vent well borings are shown in Table 2 of Appendix A. The mean coefficient of variation (CV) among the samples was 20.9 percent of the mean. A complete set of soil moisture data is found in Tables 3 and 4 of Appendix A.

### B. HYDROCARBON CONTAMINATION

#### 1. Total Hydrocarbons

During the study, 465 soil samples were analyzed for total petroleum hydrocarbons. This total includes 31 field replicates (6.7 percent of the total) and 13 trip blanks (2.8 percent). The total also includes 49 biased samples collected from continuous cores at the interfaces of sand and underlying clay, and returned to the analytical laboratory in jars. The total includes 50 soil samples which were analyzed for total hydrocarbon following screening analysis, but does not include 49 samples which were determined by screening analysis to contain less than 20 mg/kg hydrocarbons, and therefore were not analyzed by the full analytical procedure.

The distribution of sample analyses among the different rounds of sampling is shown in Table 3. Analytical reports for all samples analyzed are included in Appendix J (unpublished, available from ORNL and AFESC).

In addition to the 27 field replicates, 18 samples were analyzed in duplicate in the analytical laboratory by removal of a second soil aliquot from the core, re-extraction, and reanalysis. The latter replicates thus represent a measure of composite variability introduced both by the

sampling/handling/extraction/analysis procedure, and by soil heterogeneity on the scale of several inches. Field replicates include these sources of variability, plus soil heterogeneity on the scale of 6 to 12 inches.

Field and laboratory replicates are summarized in Table 5 of Appendix A. Of the 15 laboratory duplicate analyses of pre-venting soil samples in which hydrocarbons were detected, the mean coefficient of variation (CV) was 26 percent of the mean. The CV appears unrelated to hydrocarbon concentration, as would be expected if variance is directly related to the hydrocarbon concentration. As would be expected, logarithmic transformation appears to equalize the standard error (SE) of analytical means.

Field replicates, as would be expected, had a larger variation than did laboratory replicates. Of the 19 replicate pairs of pre-venting soil samples which contained hydrocarbons above the detection limit (20 mg/kg), the mean CV was 41.6 percent. However, at least one sample pair (871109-152 and -153) were visibly different in the soil horizon sampled. If this sample pair is not considered, the mean CV is reduced to 35.7 percent.

TABLE 3. SUMMARY OF LABORATORY ANALYSES FOR TOTAL HYDROCARBONS CONDUCTED DURING THE HILL AFB SOIL VENTING DEMONSTRATION

BOREHOLE NOS.	CORES	BIASED SAMPLES	FIELD REPLICATES	TRIP BLANKS	TOTALS
PRE-VENTING					
BH1 to BH30	43	13	5	3	64
BH31, 41	22	0	2	2	26
BH42 to 44	24	7	0	2	33
V1 to V15, E, Y	143	20	11	1	175 <sup>a</sup>
P1 to P12	39	0	0	1	40 <sup>b</sup>
POST-VENTING					
V1A to V15A, E	92 <sup>c</sup>	9	9	2	112
P1A to P6A	13	0	0	2	15
TOTAL	376	49	27	13	465

<sup>a</sup>Does not include 14 laboratory duplicate analyses.

<sup>b</sup>Does not include 4 laboratory duplicate analyses.

<sup>c</sup>Includes 4 hand-augered core samples.

### **a. Beneath Excavated Tanks**

Analyses of samples collected from the excavation are summarized in Table 6 of Appendix A. Of the 30 boreholes cored in this area, 14 were sampled for hydrocarbon analysis. Most of the borings were sampled at depth intervals of 15.5 to 16.5 feet (4.7 to 5.0 meters) BLS, 21.5 to 22.5 feet (6.6 to 6.9 meters) BLS, and at the interface between sand and the underlying clay [generally 26 to 27 feet (7.9 to 8.2 meters) BLS]. One borehole (16) was sampled at 1-foot (0.3-meter) intervals to completion at 31 feet (9.4 meters) BLS.

Because the sampling procedure used during this initial round of sampling resulted in loss of volatile components (Section III.B.3), the absolute values of hydrocarbons are probably underestimated in the analytical data by as much as 20 to 25 percent. These analytical values should therefore be used to provide a qualitative delineation of the extent of contamination, and as a semiquantitative estimate of pre-venting hydrocarbon levels.

Total hydrocarbons in excavation samples ranged from below detection (100 mg/kg for early samples) to 6400 mg/kg. Concentrations were highest in the upper samples [i.e., 15 to 24 feet (4.6 to 7.3 meters) BLS]; the highest value in a borehole occurred at the 26- to 27-foot (7.9- to 8.2-meter) depth only in borehole 1. In borehole 16, which penetrated about 7 feet (2.1 meters) into the underlying clay layer, hydrocarbon concentrations were higher in sand than in the clay, but were detectable at levels of 100 to 800 mg/kg at all depths sampled within the clay. With the exception of isolated "hot spots," highest concentrations occurred in the borings just south of the middle of the tank excavation (i.e., 12, 16, 18, 23, and 24). No contamination was detected below the upper soil layer in samples from the northernmost borings (28, 29, or 30).

### **b. Deep Exploratory Boreholes**

To assess the potential that fuel residues had penetrated into the clay layer beneath the tanks or other clay layers beneath the site, or had extended further to the east than the boundary of the tank excavation, three borings (42, 43, and 44) were augered and sampled in June 1988 (Figure 10). Although these borings were sampled at 5-foot (1.5-meter) intervals, to address the objectives outlined above only samples from depths below 50 feet (15.2 meters) BLS (along with several samples which produced strong petroleum odors during sampling) were analyzed.

Results of these analyses are summarized in Table 7 of Appendix A. At least one sample collected at depths of 6 to 16.5 feet (1.8 to 5.0 meters) BLS from each borehole had detectable hydrocarbons, with levels ranging as high as 1780 mg/kg. In contrast, no hydrocarbons were detected in any sample from the three boreholes at depths greater than 50 feet (15.2 meters) BLS. The results suggest that hydrocarbons may be present at low concentrations east of the tank excavation in the upper soil zone, but confirm that the fuel did not penetrate into the clay layer beneath the eastern portion of the site.

### **c. Vertical Vent Area**

Borings sampled during vent well installation are shown in Figure 11: Analyses of samples collected during boring are summarized in Table 8 of Appendix A. Analyzed hydrocarbon concentrations range from less than 20 mg/kg (the detection limit by later improved analyses) to a

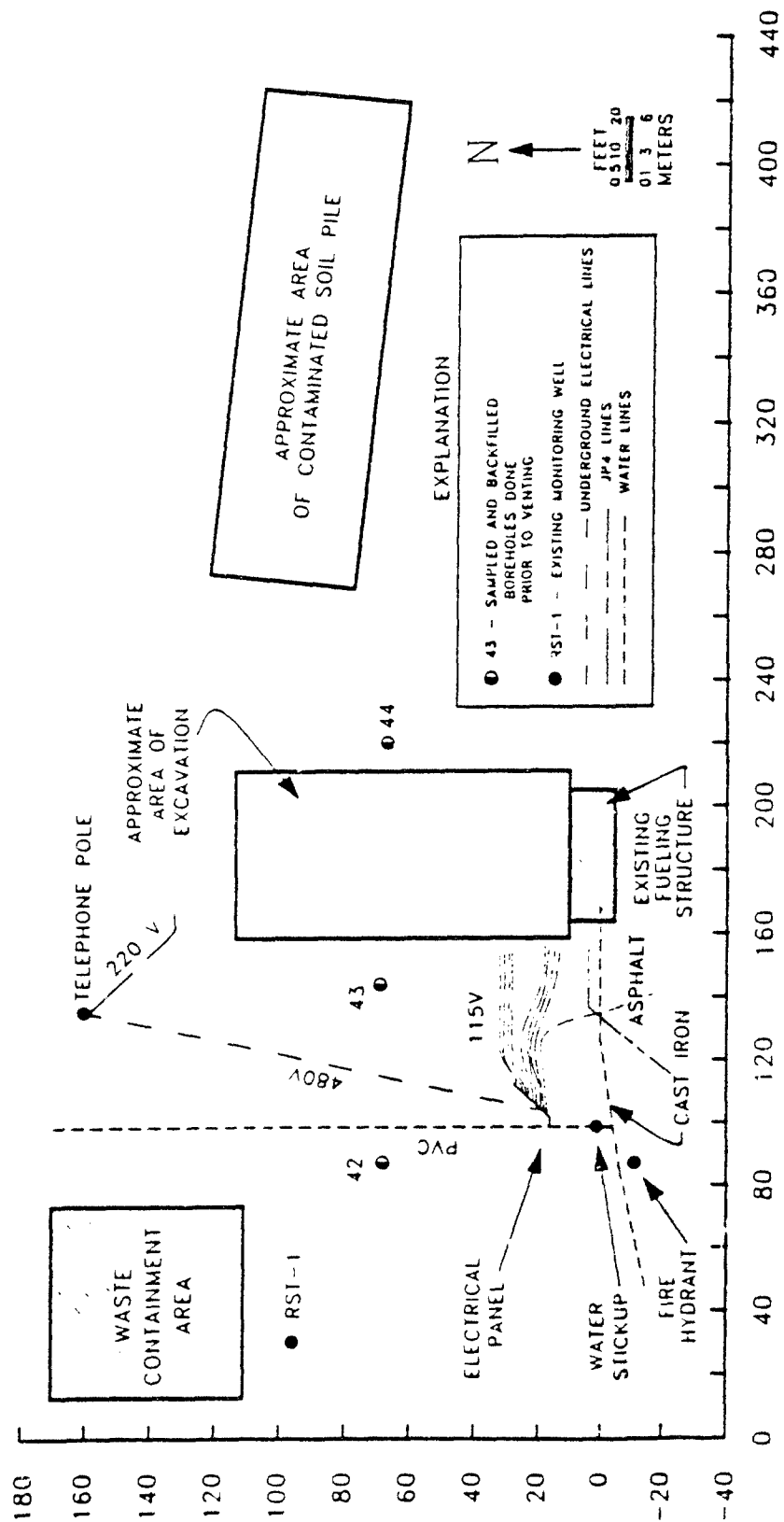


Figure 10. Locations of Borings BH41-44 at the Fuel Spill Site, Drilled for Characterization of the Extent of Eastward and Downward Migration of Fuel Contamination.

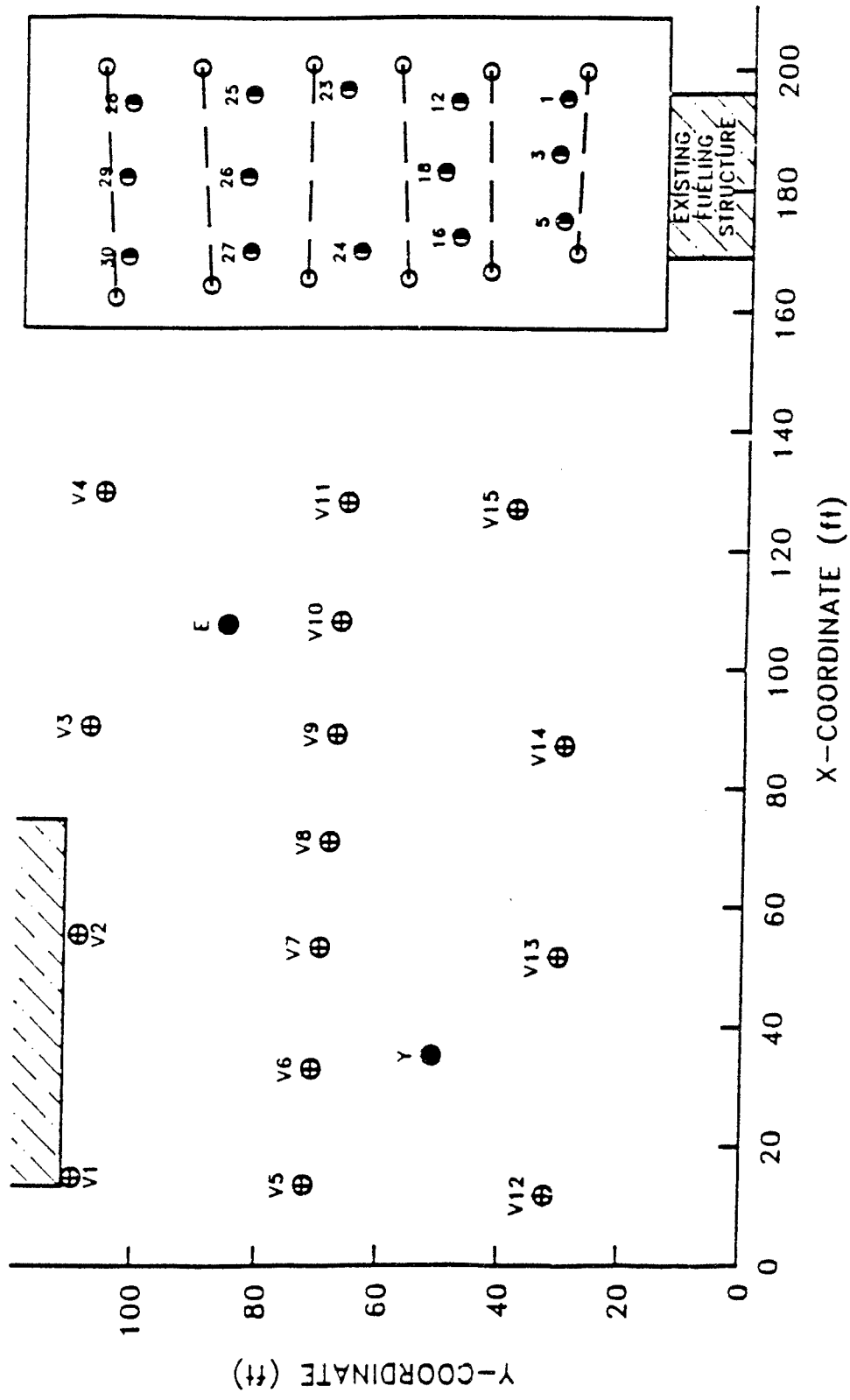


Figure 11. Locations of Vent Well and Pressure Monitoring Point Borings Which Were Sampled During Pre-Venting Characterization.

sample from V10 containing 20,400 mg/kg (more than 2 percent by weight). Following the initial round of analyses, remaining samples were screened for hydrocarbon content by headspace analysis (Section II.F.). Those samples identified as containing less than 20 mg/kg hydrocarbons were not analyzed further; the hydrocarbon concentrations of these analyses appear in parentheses in Table 8 of Appendix A.

Concentrations were highest in samples from borings V2-4, V6, V9-11, and E. All of these are located across the northern and central/eastern portion of the site, and are generally correlated with the SAIC pre-boring soil vapor survey results (Section I.B.2.c). Highest hydrocarbon levels were generally found at the upper surface of clay layers. The following biased samples were collected at the sand/clay interface: 23.5 to 25 feet (7.2 to 7.6 meters) in V2, 37.5 to 38 feet (11.4 to 11.6 meters) in V3, 17.5 to 18 feet (5.3 to 5.5 meters) in V4, 46.5 to 47 feet (14.2 to 14.3 meters) in V8, 38.5 to 39 feet (11.7 to 11.9 meters) in V10, and 35.5 to 36 feet (10.8 to 11.0 meters) in V11. High hydrocarbon levels at these interfaces may represent "pooling" of fuel during penetration downward under the force of gravity. Sharp gradients were sometimes observed above such layers, such as in the two "replicate" samples from 23.5 to 25 feet (7.2 to 7.6 meters) in V2; the lower sample (5700 mg/kg) was collected at the interface between sand and clay, while the "replicate" sample (70 mg/kg) represents a bulk sand sample from the middle split-spoon liner collected 6 inches (15 cm) higher. The 80-fold difference between these two analyses is far higher than expected, and probably represents a real hydrocarbon concentration gradient at the sand/clay interface.

#### d. Pile

Locations of borings in the pile for pre-venting and post-venting sample collection are shown in Figure 12. Analyses of pre-venting samples from the excavated pile are summarized in Table 9 of Appendix A. Total hydrocarbons range from undetectable (less than 20 mg/kg) to 3450 mg/kg. Highest concentrations were observed in the western end of the pile (borings P1-P6); the highest value determined in the eastern half of the pile was 65 mg/kg. In borings P1-P6, the maximum value in each boring occurred in the middle or lower depth, suggesting that upper layers may have been depleted in hydrocarbons due to volatilization prior to venting.

#### 2. Benzene, Toluene, and Xylene (BTX)

Concentrations of BTX were determined in the extracts of nine soil samples (plus a duplicate) from the pre-venting sampling campaign. Samples were selected for analysis on the basis of (1) high total hydrocarbon concentrations and (2) being representative of different areas of the vertical vented site. Sample results are summarized in Table 10 of Appendix A.

Benzene was not detected (20 mg/kg detection limit) in any of the samples. Toluene and xylenes were found at levels of up to 308 and 600 mg/kg, respectively. The BTX compounds constituted from less than 0.2 percent to more than 20 percent of the total hydrocarbons in individual samples (mean: 9.0 percent).

#### 3. Hydrocarbon Boiling Ranges

Absolute concentrations and relative proportions of hydrocarbon boiling ranges for several representative samples from the sub-excavation borings, the pile, and the vent well borings are summarized in Tables 11 and 12 of Appendix A. In each case the predominant hydrocarbons are

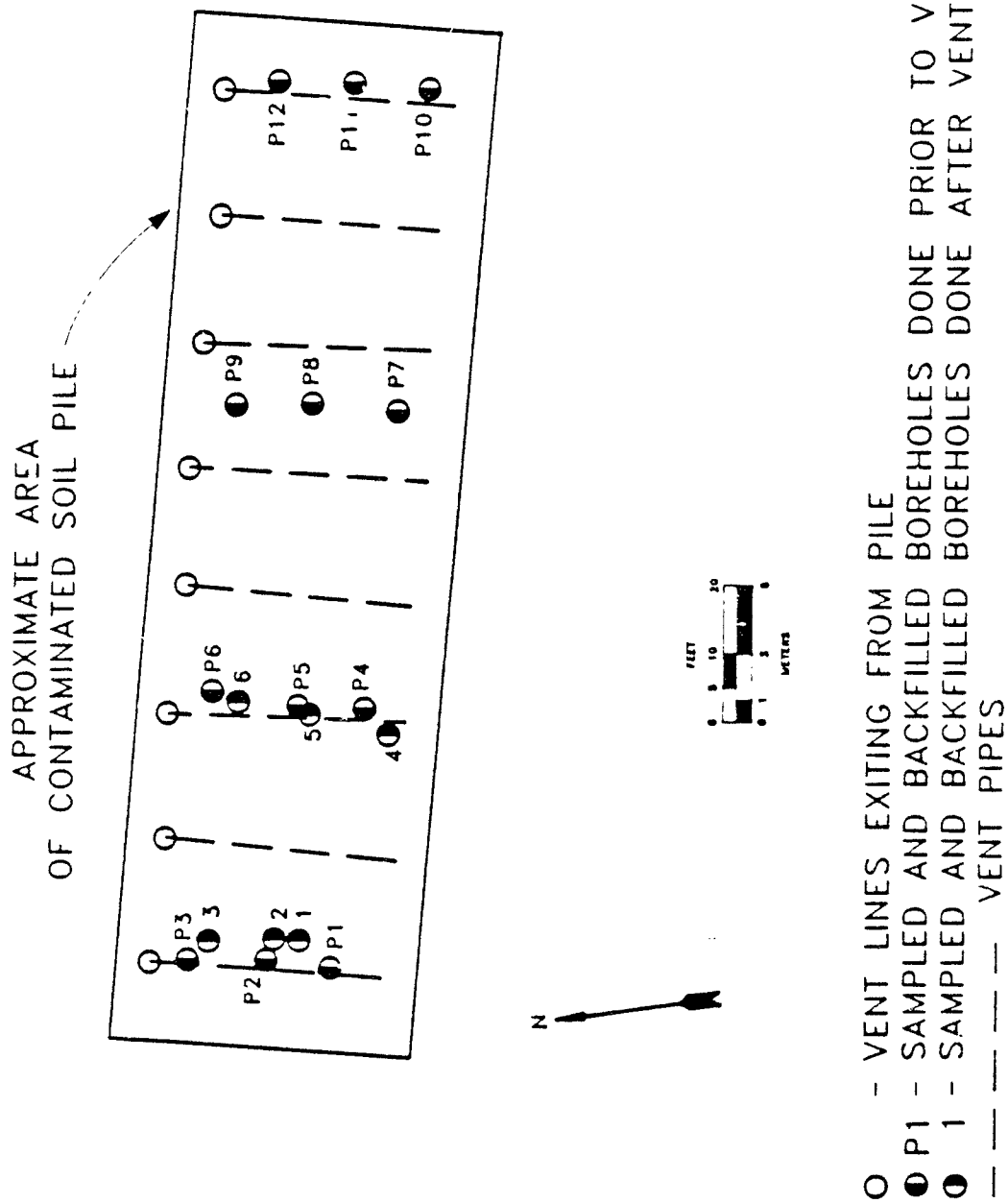


Figure 12. Locations of Pre- and Post-Venting Borings in the Soil Pile.

fractions whose boiling range corresponds to that of 9-, 10-, and 11-carbon aliphatic hydrocarbons (referred to hereafter as C-9, C-10 and C-11 hydrocarbons, respectively).

Hydrocarbon distributions in samples from the vertical vent borings, relative to that of a JP-4 standard, are shown in Figures 13 through 16. Figure 13 shows that the distribution in 3 samples from vent wells V4, V15, and pressure monitoring point E are virtually identical. A nearly identical pattern is also seen in a V11 sample (Figure 14), and in samples collected earlier from borings 31 (V7) and 41 (Figure 15). In each of the 6 samples the hydrocarbon ranges appear to be depleted of the C-6 through C-9 fractions, which form the predominant portion of the JP-4 standard. The C-12 through C-15 fractions similarly appear to be depleted in the 6 soil samples.

A quite different hydrocarbon distribution pattern is illustrated in Figure 16, which shows a comparison between a sample from boring V2 and boring E. The latter serves as a representative of the more common pattern found in the vertically vented area. In comparison, the V2 sample is even more significantly depleted in the lighter C-7, -8, and -9 hydrocarbons. Visual comparison of the chromatographic scan of a V2 sample with that from E (Figure 17) demonstrates the difference in appearance of the two hydrocarbon distributions. The difference is sufficiently great to suggest that the chromatograms represent different starting materials. Because V2 is adjacent to the waste oil storage tanks, the difference in hydrocarbon distributions may indicate that a different oil, other than JP-4, was spilled in the vicinity of V2 at some point in the past.

Figures 18 and 19 show samples that for different reasons received substantially greater exposure to the atmosphere than did the samples shown in Figures 13 through 16. Three representative hydrocarbon distributions from samples collected beneath the tanks are shown in Figure 18. The hydrocarbon distribution from boring 26 appears similar to those of the vent well borings, although with a higher proportion of C-13 through C-16 hydrocarbons. In contrast to the vent boring samples, however, the samples from borings 5 and 16 show nearly equal proportions of C-10 and C-11 hydrocarbons. Both samples are depleted in C-7 through C-9 hydrocarbons relative to Figures 13 through 15; in boring 5, no C-7, -8, or -9 hydrocarbons are present at all. The reduction of more volatile hydrocarbon fractions may be due to aeration during sample collection; these initial samples were collected with a bucket auger, mixed with a spatula, and packed into jars for shipment. It seems quite likely that the depletion of lighter hydrocarbon fractions is therefore due to sampling, and does not reflect actual differences in the soil hydrocarbon distribution relative to the vent borings. Relative to samples from V4, V15, and E, the depleted C-7 through C-9 hydrocarbons may constitute an underestimate of the actual hydrocarbon concentration of as much as 20 to 25 percent.

Two hydrocarbon distributions from pre-venting pile samples are shown in Figure 19. In comparison with a representative sample from the vertical borings (E), both are depleted in lighter (C-7 through C-9) hydrocarbons. The pile soil was removed by excavation and mounded at the pile site; in this process the soil undoubtedly was aerated to some extent, which may account for the reduced relative proportion of lighter hydrocarbons.

### C. INITIAL HYDROCARBON MASS

To determine the initial hydrocarbon mass in the three vented areas (i. e., the vertical vent zone, the lateral vent zone beneath the tanks, and the pile), each area was subdivided into sub-areas, each



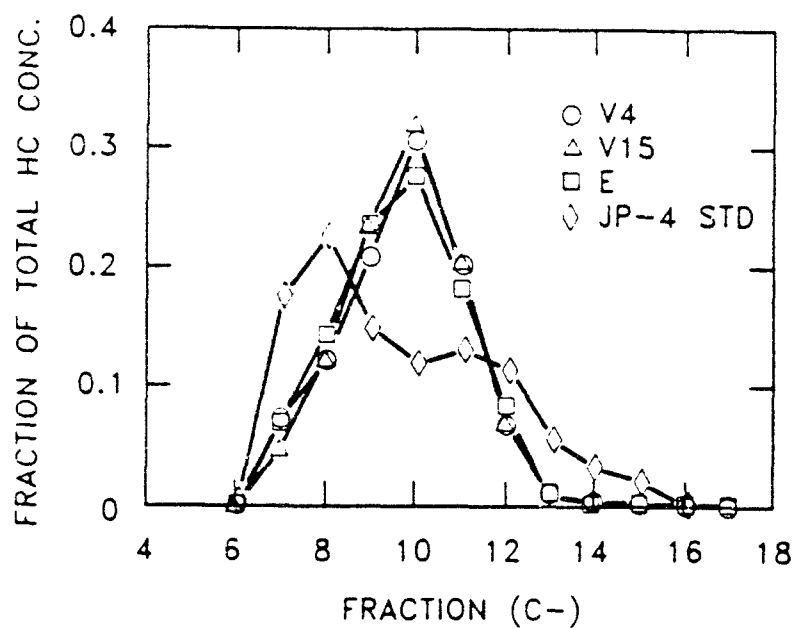


Figure 13. Proportions of Hydrocarbons in Fractions Identified by Apparent Carbon Number in Representative Samples from Pre-Venting Borings V4, V15, and E from the Vertical Vent Area. Authentic JP-4 Standard Profile Included for Comparison.

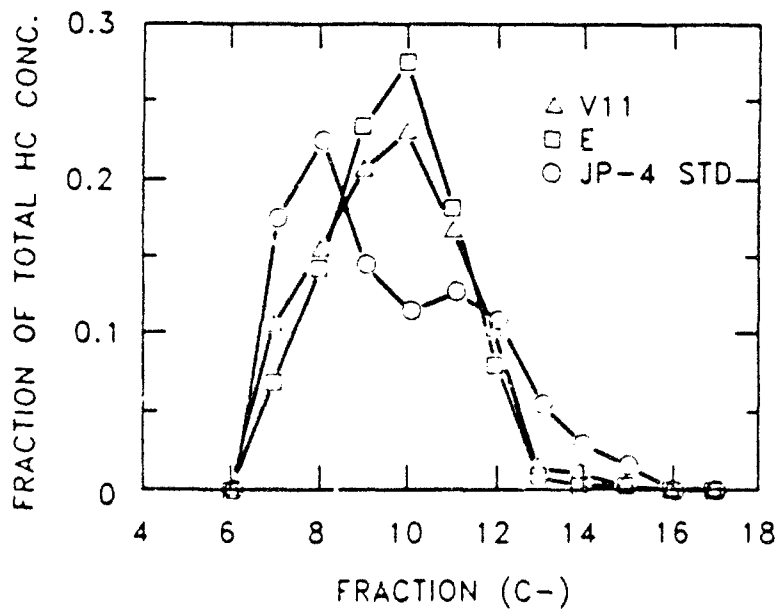


Figure 14. Proportions of Hydrocarbons in Fractions Identified by Apparent Carbon Number in Representative Samples from Pre-Venting Borings V11 and E From the Vertical Vent Area. Authentic JP-4 Standard Profile Included for Comparison.

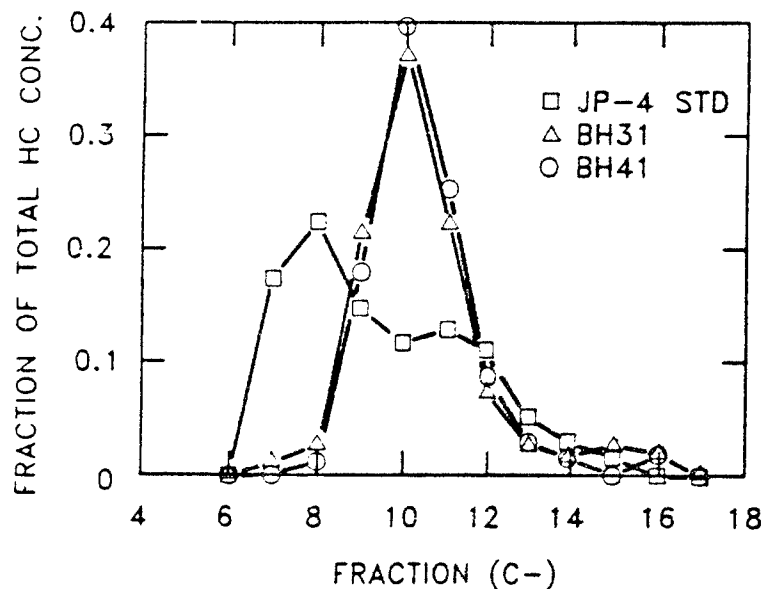


Figure 15. Proportions of Hydrocarbons in Fractions Identified by Apparent Carbon Number in Representative Samples From Pre-Venting Borings BH31 and BH41 From the Vertical Vent Area. Authentic JP-4 Standard Profile Included for Comparison.

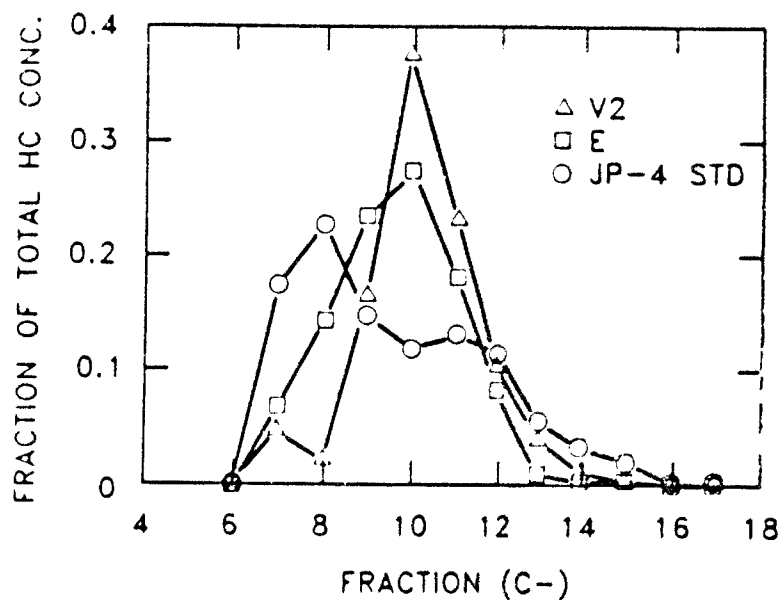


Figure 16. Comparison of Hydrocarbon Profile From a Sample From Boring V2 With a Profile (E) Representative of Most of the Vertical Vent Samples.

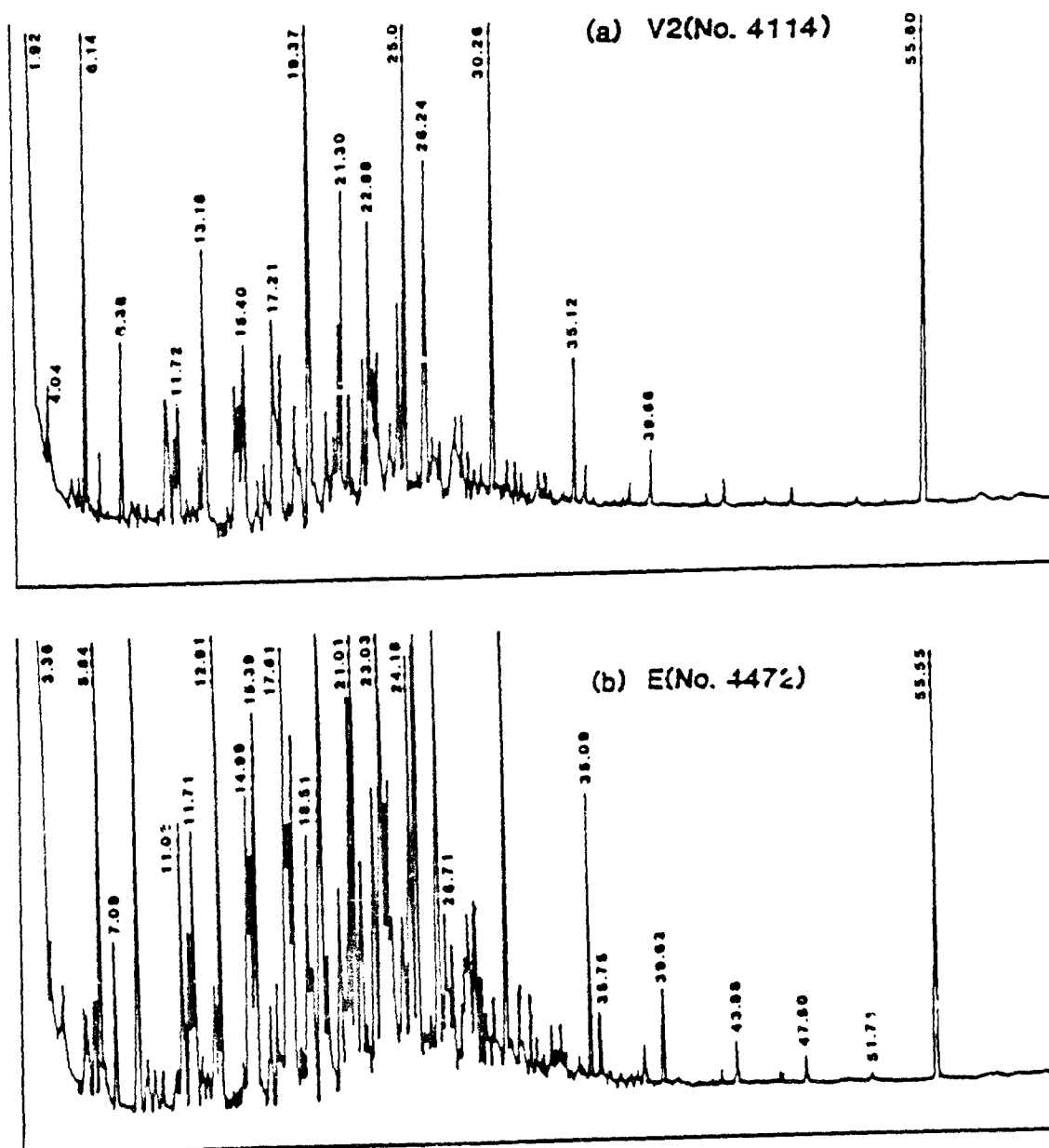


Figure 17. Comparison of Gas Chromatographic Scans of Hydrocarbon Extracts From Boring V2 With a Scan (E) Representative of Most of the Vertical Vent Samples.

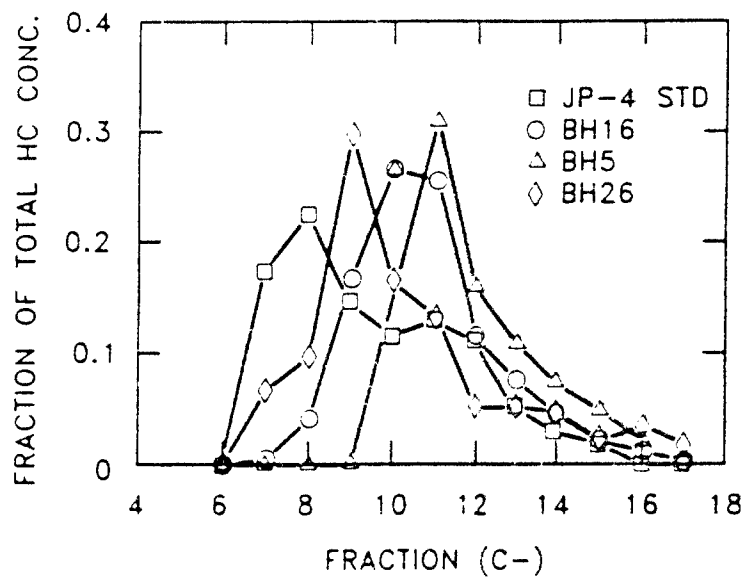


Figure 18. Proportions of Hydrocarbons in Fractions Identified by Apparent Carbon Number in Representative Samples From Sub-Tank Excavation Borings BH5, BH16, and BH26. Authentic JP-4 Standard Profile Included for Comparison.

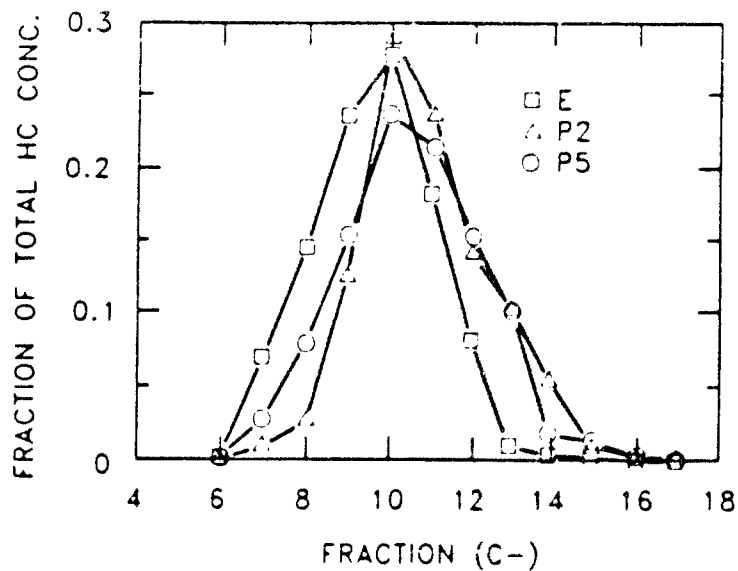


Figure 19. Comparison of Hydrocarbon Profile From a Sample From Pile Borings P2 and P5 With a Profile (E) Representative of Most of the Vertical Vent Samples.

containing a single boring. The volumes beneath these areas were then divided into "slices" whose lower boundary (in depth BLS) coincided with the bottom of a core sample interval. The hydrocarbon concentration of each volumetric subsection could thus be represented by the analyzed hydrocarbon concentration of a single core analysis (or by the mean of a field or laboratory replicate pair of analyses). Biased samples were considered representative of the sampled zones in the same manner as samples obtained at regular spacing.

Because the hydrocarbon concentrations were reported on an as-received (i. e., wet weight) basis, the concentration of each volumetric subsection was converted to a dry-weight basis before determination of the hydrocarbon mass within each soil volume. The mean dry bulk density determined for the site (1.67 grams/cm<sup>3</sup>) was used as a constant throughout the analyses.

### 1. Vertical Vent Area

The areas defined for the vertical vent area are shown in Figure 20. The interior boundaries of each rectangular area are the approximate midpoints of the distance between adjacent borings. Both boreholes E and Y, which were sampled, are included in the analysis. Boreholes 42 and 43, which were sampled but only analyzed intermittently, are not included in the analysis. The outer boundaries of the area are defined as a distance from the outermost borings approximately equal to the 20-foot (6.1-meter) distance between adjacent borings.

Results of the analysis for the vertical vent well soil volume are shown in Table 4. This table represents a summary of the analysis; complete worksheets are included in Appendix G, in which the pre-venting and post-venting fuel masses are compared in evaluation of the effectiveness of the venting operation. The total pre-venting hydrocarbon mass in the vertical vent area was calculated to be 30,760 pounds (13,952 kg). Of this figure, more than 65 percent occurs in the four sub-areas of highest hydrocarbon mass (V2, V4, V9, and V10). The four vent sub-areas along the northern boundary constituted 41.1 percent of the total mass, while the three along the southern border (V13 through V15) comprised only 3.1 percent of the total. The three western most sub-areas (V1, V5, and V12) comprised only 0.8 percent of the total hydrocarbon mass.

The total fuel mass in the vertical vent zone was also determined by computerized calculation of the volumes (courtesy of Dynamic Graphics, Inc.) of nested equal-concentration "shells" and calculating the hydrocarbon concentration on the basis of the computed soil masses (assuming a bulk density of 1.67 grams/cm<sup>3</sup>). Results of this calculation are shown in Table 5. The total hydrocarbon mass is computed to be 38,780 pounds (17,590 kg), or approximately 26 percent higher than the estimate computed on the basis of rectangular sub-volumes. However, the latter figure does not take into account the water content of the soil. If a mean moisture content of 9 percent is assumed, the corrected mass would be (17,590/1.09), or 16,138 kg. Because this value is necessarily based on computer interpolation, it is a step further removed from the initial concentration data than is the method of rectangular sub-volumes. The figure of 30,760 pounds (13,952) kg is therefore more directly defensible, and will be used throughout subsequent calculations of hydrocarbon removal efficiency (Section V.J).

### 2. Area Beneath Tank Excavation

The area beneath the tank excavation was subdivided into 14 sub-areas in the same manner as the vertical well area, with each sub-area approximately centered on a borehole. The layout of

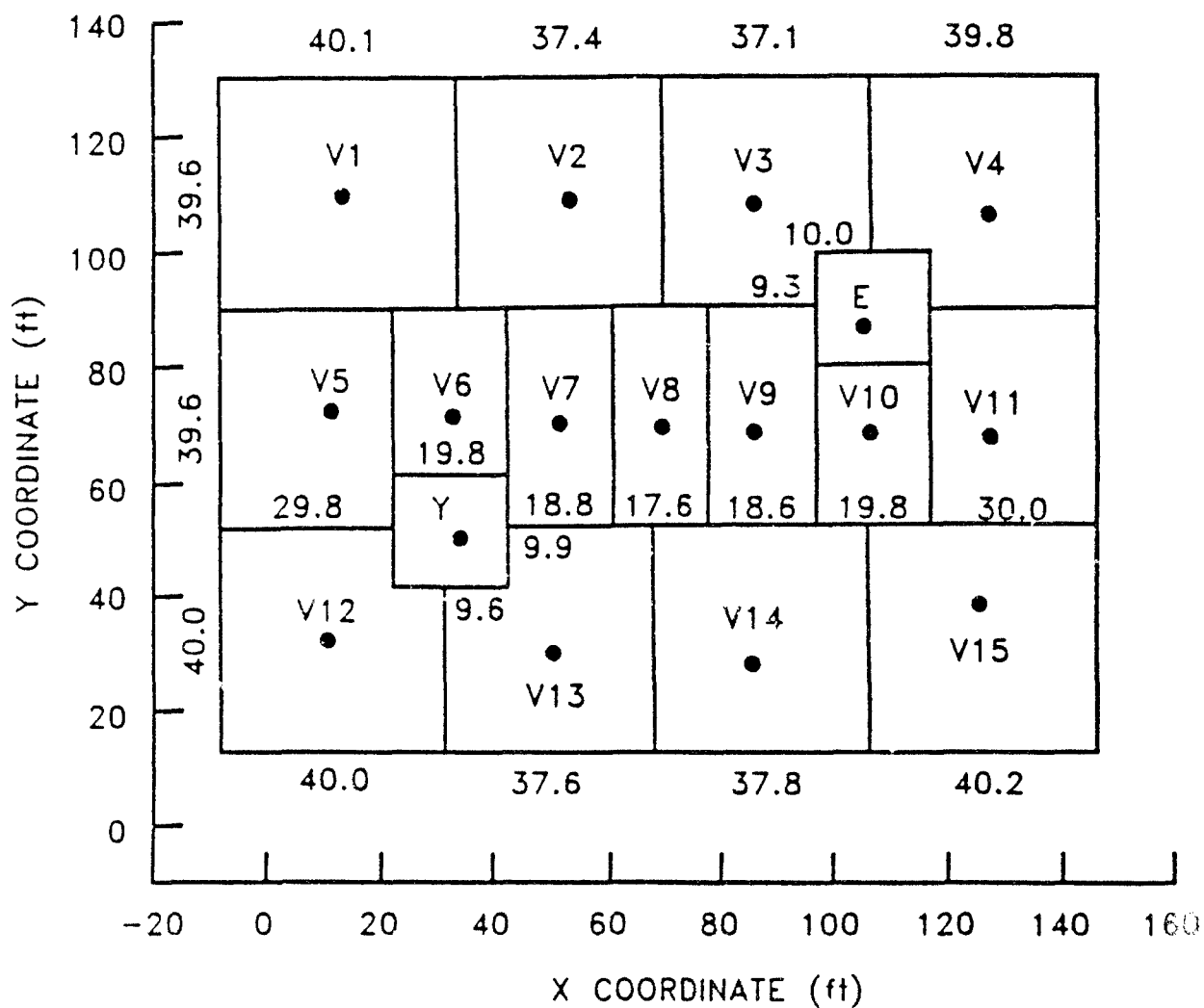


Figure 20. Schematic Diagram of Sub-Areas at the Vertical Vent Area of the Spill Site, Delineated For Determination of Total Mass of Residual Hydrocarbons. Axes Shown Are Those of the Project Grid; Units of All Dimensions Are in Feet.

TABLE 4. SUMMARY OF PRE-VENTING HYDROCARBON MASSES IN THE VERTICAL VENT AREA

AREA	FUEL MASS (kg)	FRACTION OF TOTAL MASS (%)
V1	38.7	0.3
V2	2652	18.9
V3	1170	8.4
V4	1878	13.5
V5	28.7	0.2
V6	1001	7.2
V7	274	2.0
V8	261	1.9
V9	2461	17.5
V10	2124	15.2
V11	722	5.2
V12	36.0	0.3
V13	31.3	0.2
V14	193	1.4
V15	204	1.5
E	864	6.2
Y	12.9	0.1
TOTAL	13,952	100.0

sub-areas is shown in Figure 21. Boundaries between sub-areas were defined to bisect the distance between adjacent boreholes. The central area, in which no borehole could be drilled because of a large concrete block, was not used in the analysis. Fuel concentrations were converted to a dry-weight basis by applying mean moisture contents determined on representative samples [0.09 and 0.27 for samples above and below 10-foot (3.0-meter) depth, respectively].

Detailed results are shown in Table 13 of Appendix A. The total fuel mass estimated for the soil volume was 7880 pounds (3574 kg). More than 67 percent of this figure is in the central-south

TABLE 5. PRE-VENTING FUEL MASS IN VERTICAL VENT AREA (ESTIMATED BY DYNAMIC GRAPHICS, INC.)

JP-4 CONCENTRATION (mg/kg)			SOIL MASS (kg)	FUEL MASS (kg)
LOWER	UPPER	MEAN		
0	20	10	26,310,579.41	263.11
21	50	35	2,421,856.36	84.76
51	100	75	3,145,957.28	235.95
101	200	150	3,937,656.07	590.65
201	300	250	2,827,240.31	706.81
301	400	350	2,306,037.11	807.11
401	500	450	1,965,214.74	884.35
501	600	550	1,737,605.71	955.68
601	700	650	1,547,449.12	1005.84
701	800	750	1,341,940.76	1006.46
801	900	850	1,201,391.27	1021.18
901	1000	950	1,107,469.32	1052.10
1001	1500	1250	3,530,588.44	4413.24
1501	2000	1750	1,426,058.58	2495.60
2001	2500	2250	539,335.88	1213.51
2501	3000	2750	173,177.90	476.24
3001	4000	3500	77,841.85	272.45
4001	5000	4500	14,197.78	63.89
5001	7500	6250	6,124.62	38.28
7501	10000	8750	312.14	2.73
			<b>TOTAL</b>	17,590 (38,786 lb)



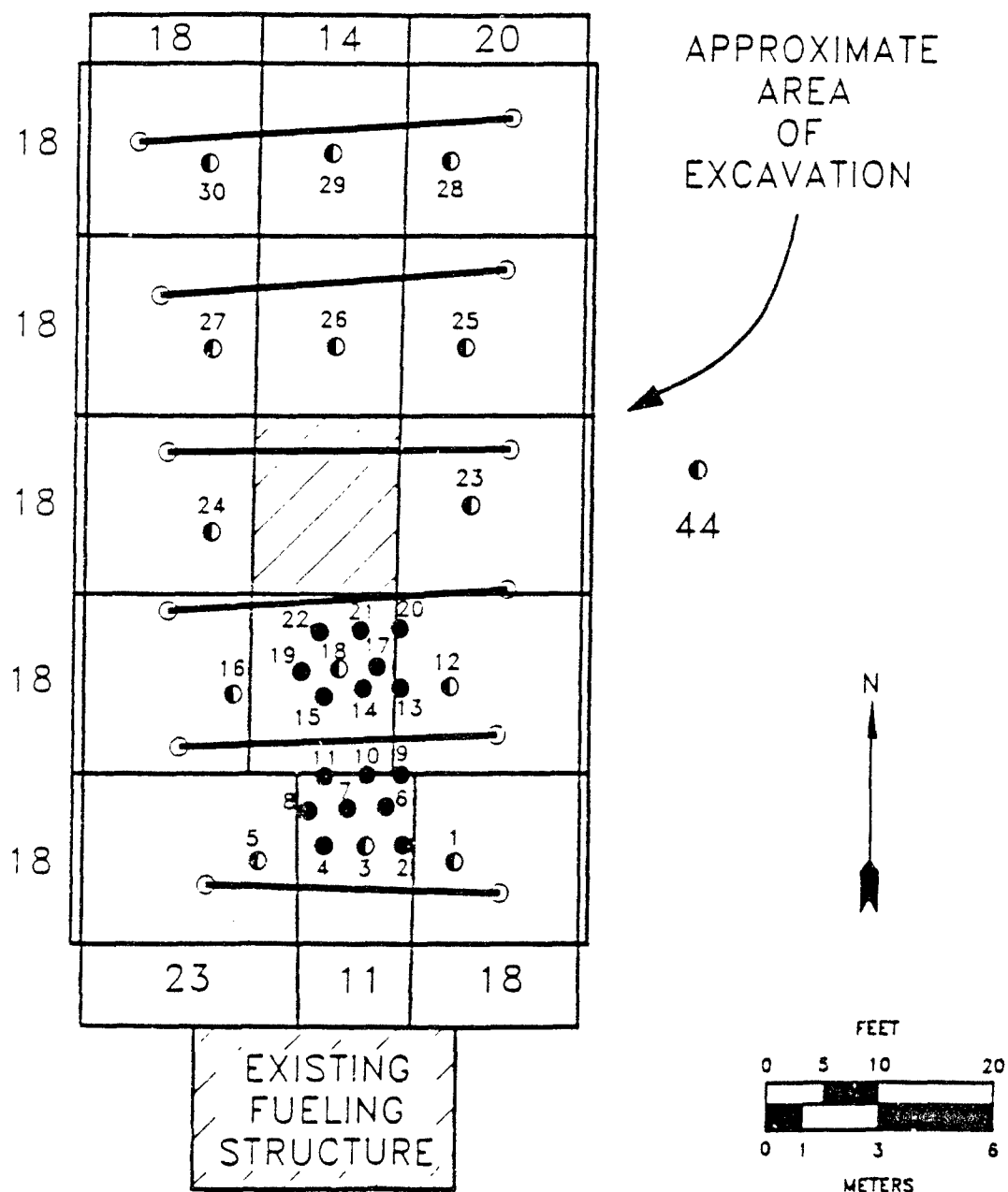


Figure 21. Schematic Diagram of Sub-Areas at the Sub-Tank Excavation Area of the Spill Site, Delineated for Determination of Total Mass of Residual Hydrocarbons. All Dimensions Shown in Feet.

sub-areas (borings 12, 16, 18, 23, and 24), approximately beneath the location of the valve which caused the 1985 spill. As pointed out in Section III.B.1(a), hydrocarbon concentrations in this area probably underestimate the actual fuel concentrations by 20 to 25 percent due evaporative loss of lower-boiling hydrocarbons (C-6 to C-9) during sampling. A more realistic estimate of the fuel content in this area, therefore, may be between 9456 and 9850 pounds (4289 and 4468 kg). These figures would still be less than 32 percent of the vertical vent area total of 30,760 pounds (13,952 kg).

### 3. Pile

To calculate the volume of hydrocarbons in the pile, the trapezoidal solid pile was approximated as three rectangular solid layers (Figure 22). Each layer was subdivided into 12 sub-areas, based on the locations of the sampled boreholes. The thickness of each sub-volume was designated as extending to the bottom of the soil sample, the hydrocarbon analysis of which was used to determine the soil hydrocarbon mass. Because the pile was thicker along the southern side than the northern, sub-volumes in the lowest layer decreased in thickness from the southern edge (P1, 4, 7, and 10) toward the north.

Results are shown in Table 6. For each borehole, data from the three layers are combined to give an estimate for the borehole. This table represents a summary of the analysis; complete worksheets are included in Appendix G, in which the pre- and post-venting fuel masses in the pile are compared in evaluation of the effectiveness of the venting operation. The total pre-venting fuel mass in the pile is calculated as 2190 pounds (994 kg). Of this figure, all but 2.3 percent is found in the western half of the pile (P1 through P6).

### 4. Totals

The total mass of fuel hydrocarbons calculated to be present in the soil in the three volumes to be vented is: vertical vents - 30,760 pounds (13,952 kg), beneath tank excavation - 7879 pounds (3574 kg), and pile - 2190 pounds (994 kg). Thus, the relative fractions contributed by the vertical vent, tank excavation and pile areas are 75.3 percent, 19.3 percent and 5.4 percent, respectively. If the estimate of fuel mass beneath the tank excavation is increased by 25 percent to account for underestimation of the light hydrocarbon fractions, the total fuel mass increased by 1970 pounds (894 kg) to a total of 42,808 pounds (19,414 kg). The relative fractions contributed by the vertical vent, tank excavation, and pile areas are thus 71.9 percent, 23.0 percent, and 5.1 percent, respectively.

Based upon the finite number of soil samples that could be economically gathered and analyzed, pre-test sampling has accounted for approximately 25 percent of the estimated original spill. There is no way of knowing the initial spill size or the quantity of JP-4 that volatilized during the three years which elapsed between the spill and venting operations. Section V.I. contains a more complete discussion of the hydrocarbon mass balance.

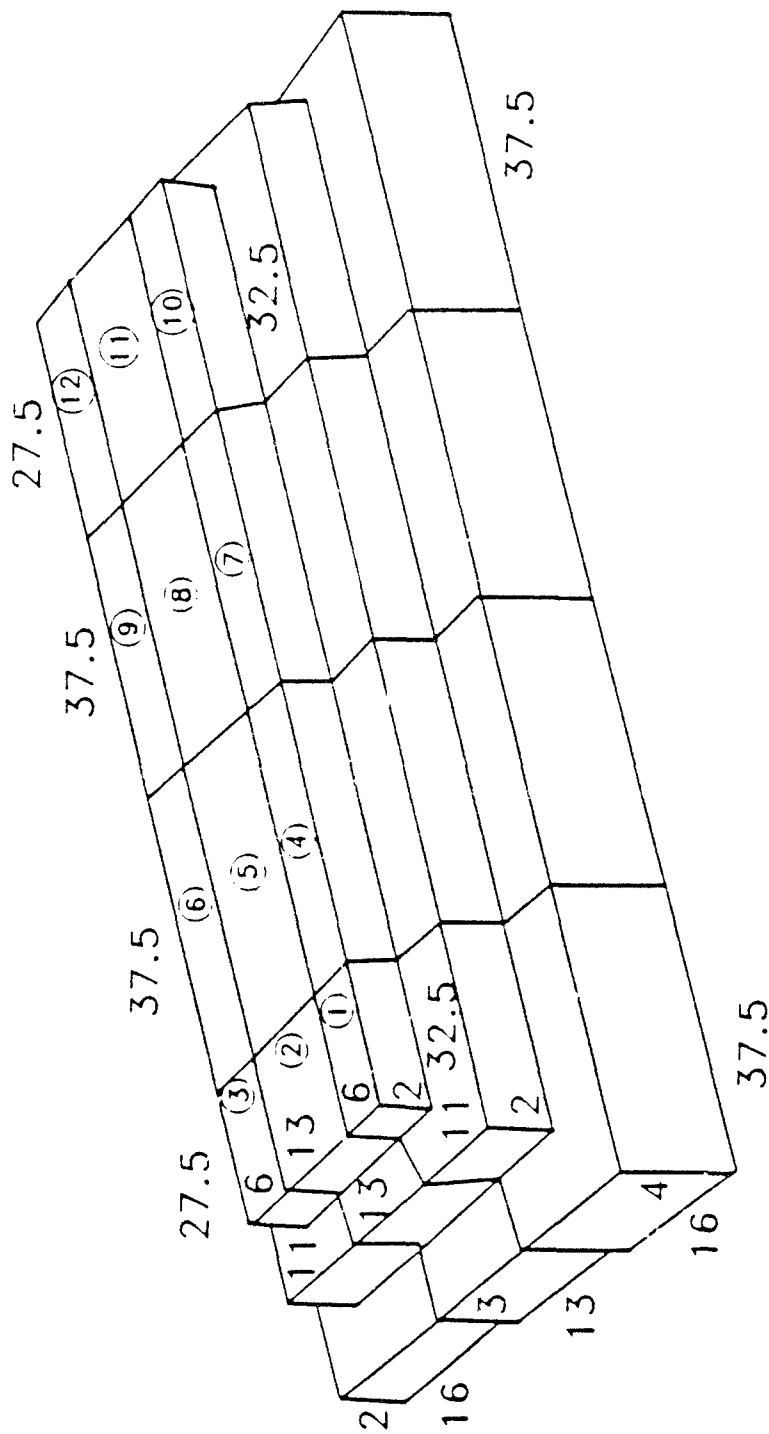


Figure 22. Schematic Diagram of Sub-Volumes of the Soil Pile Area of the Spill Site, Delineated for Determination of Total mass of Residual Hydrocarbons. All Dimensions Shown in Feet. Sub-Area Designations are Those of Pile Borings (in Circles).

TABLE 6. SUMMARY OF PRE-VENTING HYDROCARBON MASSES IN THE PILE

AREA	FUEL MASS (kg)	PERCENTAGE OF TOTAL MASS (percent)
P1	171	17.2
P2	87.5	8.8
P3	249	25.1
P4	42.6	4.3
P5	190	19.1
P6	230	23.2
P7	4.1	0.4
P8	6.2	0.6
P9	4.0	0.4
P10	1.6	0.2
P11	1.5	0.2
P12	4.7	0.5
TOTAL	994	100.0

## SECTION IV

### PILOT STUDIES

#### A. INTRODUCTION

The first steps in this field implementation of ISSV were to install and operate a pilot venting system and perform supporting bench studies for determination of design data for the full-scale system. Data obtained included pressure-flow rate-distance relationships and effluent gas hydrocarbon concentrations. Pressure-flow rate-distance relationships of the soil at the venting site were necessary to determine the vacuum, air extraction rate, and vent spacings needed to produce sufficient air flow for remediation. Measured effluent gas hydrocarbon concentrations provided information necessary for air emissions permitting and for specification of emissions control equipment.

This test involved the installation of a single extraction vent of the design projected for the vents of the full-scale system. Pressure measurement vents surrounding the extraction vent allowed monitoring of lateral and vertical soil vacuum distribution. Operation at several flow rates provided data for generation of characteristic curves that may be used for empirical system design and for calibration of flow models for system optimization.

Tests were also made to determine the permeability of the soil by an *in situ* method. This determination of permeability, if successful, would provide permeability values for modelling of induced flow fields in venting systems with a minimum of expense.

Prediction of effluent concentrations from *in situ* soil venting systems is difficult. Published results from other soil venting studies have shown hydrocarbon concentrations to be very high during the initial hours of operation, usually tapering off quickly after a few days as the soil gas is cleared. The initial concentration and rate of decrease of concentration in the extracted gas will depend mainly on (1) the position of the vents relative to contaminated soil, (2) the levels of contamination, and (3) the vapor pressures of the contaminants.

The single-vent test included analysis of the extraction air, both by a continuous total hydrocarbon analyzer (THA) for indication of hydrocarbon concentration level, and by a gas chromatograph via sorbent traps for speciation of contaminants. These analyses allowed selection of emissions control devices and provided information necessary for air emissions permit applications.

The single-vent test was operated under conditions imposed by the Utah Air Conservation committee as stated in letter BAQ-5943-1, 4 November 1987. The conditions of this letter limited the experiment to 100 hours of venting, not to exceed 1500 pounds (680 kg) of VOC emissions. A minimum of one grab sample per day and a brief report of our findings to the Executive Secretary of the Utah Air Conservation Committee were required.

Since the operating time of the pilot test was limited, little information would be gained for long-term operation. To help predict system behavior, soil from the site was vented in a column test. Operation of the column for several hours would simulate operation of the full-scale system for several months. It was hoped that extracted gas concentrations from the column would allow prediction of removal rates in the full-scale system and provide a basis for full-scale system design.

## B. SINGLE VENT PILOT TEST

### 1. System Design

Design of the ISSV pilot system was based mainly upon studies by R. F. Weston, Inc. (Reference 5) for the USATHAMA and by Texas Research Institute for the American Petroleum Institute (API) (Reference 3). The USATHAMA report dealt with the soil venting at a site of a trichloroethylene spill, but it provided pressure-flow rate-distance relationships for sandy soils judged to be similar to those at the Hill site. From this study, the single-vent test system was designed for a flow rate of 0.024 to 0.118 m<sup>3</sup>/second at vacuum levels up to 30,500 Pascals. The API report was the only available fully documented field study of the removal of petroleum hydrocarbons from sandy soils. This study differed from the Hill AFB because (1) it was performed at a site contaminated with gasoline rather than JP-4 jet fuel and (2) there was free fuel pooled at the water table surface, unlike the Hill site. The extraction gas concentration initially encountered in the API study was 4000 ppmv. These factors suggested that the extraction gas concentration levels encountered in the ISSV pilot test would not initially exceed the 4000 ppmv hydrocarbons average concentration, and the system was designed accordingly.

The major components of the *in situ* soil venting single-vent pilot system were:

- extraction and pressure monitoring vents,
- process equipment (blower, knock-out drum, vent-head connection, discharge), and
- analytical trailer

#### a. Extraction and Pressure Monitoring Vents

(1) Location. The approximate location of the extraction vent and pressure monitoring wells for the single vent pilot test are shown in Figure 23. The position for the extraction vent was chosen to place it as near as possible to the area of highest soil vapor hydrocarbon concentration as measured in the most recent Installation Restoration Program Phase II survey (see Section I.B.2.c.1). This position was used to provide a realistic estimate of initial effluent concentrations from the full-scale system.

The locations of the nine pressure monitoring vents were along six radial axes at distances of 3.0, 6.1, and 9.1 meters (10, 20, and 30 feet) from the central extraction vent. The radial axes were spaced at approximately 30 degree intervals. The monitoring vents were 4.6, 9.1, and 13.7 meters (15, 30, and 45 feet) deep. This distribution was chosen to minimize the effects of one vent upon another and the effects of discontinuities in the soil.

(2) Extraction Vent Design. The extraction vent borehole was augered with an 8-inch hollow-stem auger. This auger permitted later installation of the vent pipe (3.5 inches outside diameter) through the hollow stem. The vent consisted of a 12.2-meter (40-foot) length of flush-joint Schedule 40 polyvinyl chloride (PVC) screen with slot width of 0.05 cm (0.02 inches) installed at a depth of between 3 and 15.2 meters (10 and 50 feet) below ground surface and capped at the lower end (see Figure 24). Flush-joint Schedule 40 PVC was used for the riser pipe. PVC cement was used to join all PVC fittings. Stainless steel centralizers were used to maintain the riser pipe in the center of the borehole.

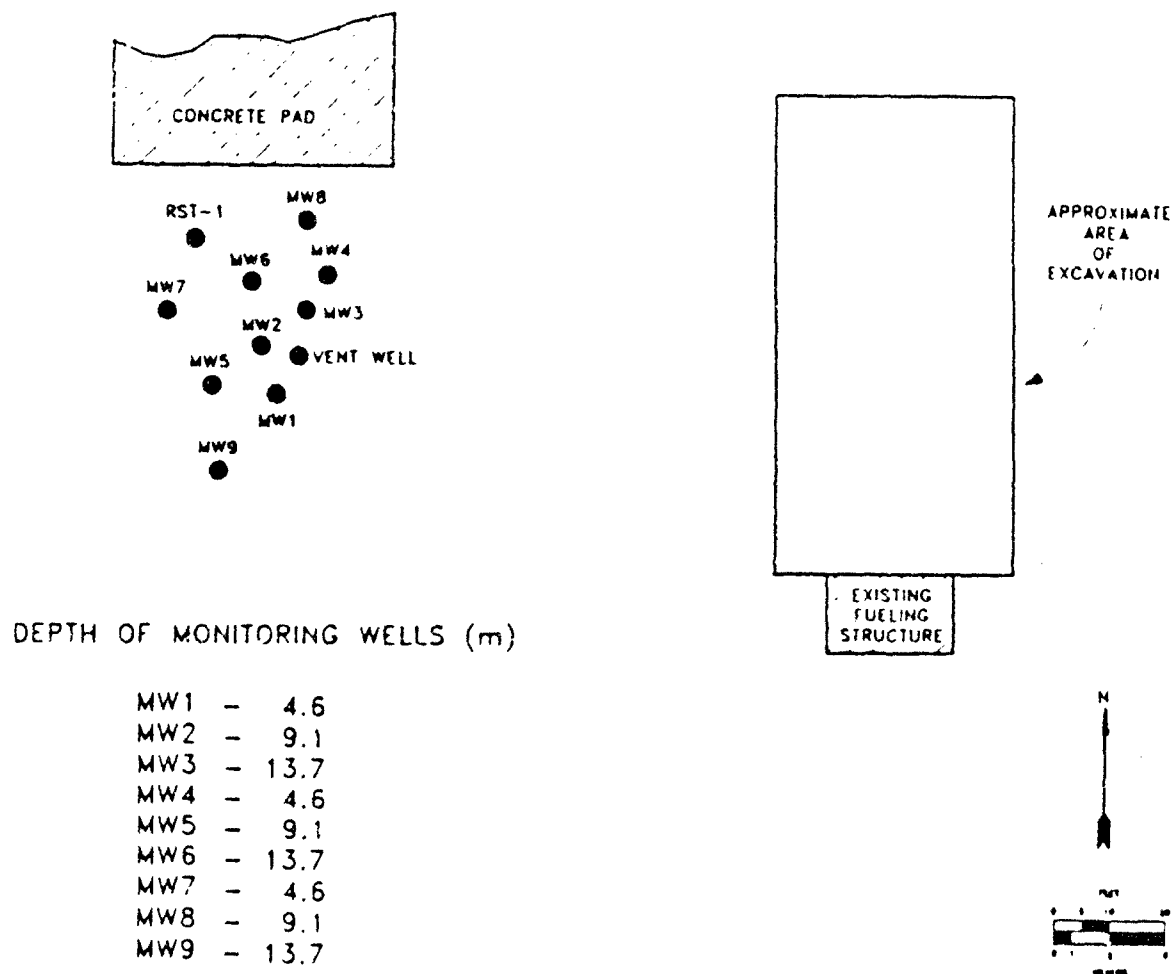


Figure 23. Position and Labeling of Monitoring Wells in Single Vent Pilot Test.

The auger hole was backfilled with coarse sand to 0.3 meters (1 foot) above the screen, using a tremie tube. A 0.3-meter (1-foot) layer of bentonite pellets was placed on top of the sand, and the hole was grouted to the surface by tremie tube with cement-bentonite grout to prevent a short-circuit path for air flow. A concrete collar at least 0.6 meter (2 feet) in diameter was installed to provide mechanical stability for the vent and to divert rainfall from penetrating down the backfilled hole. The vent extended 0.3 meter (1 foot) above the concrete collar, and was covered with a PVC cap to prevent water infiltration before system installation.

(3) Pressure Monitoring Vent Design. The pressure monitoring wells consisted of 2.54-cm (1-inch) OD flush-joint PVC which had a lower 0.6-meter (2-foot) screened section, capped at the bottom end, connected to the remaining upper section of 1-inch flush-joint PVC well casing (see Figure 25). The dead space in the pressure monitoring well was minimized by internally capping off the pipe at the top of the screened section with a PVC plug and running a 0.64-cm (1/4-inch) polyethylene tube to the surface.

The pressure monitoring wells were installed in 10.2-cm (4-inch) augered boreholes. PVC cement was used to join all subsurface PVC fittings. Stainless steel centralizers were used to maintain the riser pipe in the center of the borehole. Coarse sand was packed to a depth of 0.3 meter (1 foot) above the screens, using a tremie tube. The holes were backfilled to the surface with a 0.3-meter (1-foot) layer of bentonite pellets, followed with cement-bentonite grout. The vents extended 0.3 meter (1 foot) above-ground surface, and were capped with PVC caps to prevent water infiltration. The PVC caps were tapped with 0.64-cm (1/4-inch) tubing fittings for connection of pressure gauges.

#### b. Process Equipment

A diagram of the single-vent test system process equipment is shown in Figure 26. The equipment may be broken down into the following parts:

- vent-head connections,
- knock-out drum,
- blower, and
- discharge.

(1) Vent-Head Connections. The extraction vent pipe extended 1 foot (0.3 meter) above ground surface. This above-ground section was surrounded by a 6-inch (15.2-cm) steel vent protector. Two 1/4-inch (0.64-cm) pipe-to-tubing fittings were threaded into the vent pipe for connection to a Magnehelic differential pressure gauge and a thermocouple. This allowed measurement of vacuum and effluent air temperature at the vent head. A 3-inch (7.62-cm) schedule 40 PVC "Y" fitting was socket-welded to the vent pipe. The leg of the "Y" was angled up and was capped. The cap was tapped with a bored-out 1/4-inch (0.64-cm) tubing fitting to allow the insertion of 0.64-cm (1/4-inch) polyethylene tubing to various depths in the extraction vent.

A 3-inch (7.62 cm) PVC ball valve was fitted to the remaining connection of the "Y" to isolate the vent from the system. A 3-inch (7.62-cm) PVC tee was fitted to the ball valve which connected the 3-inch (7.62-cm) valved line to the atmosphere for clearing the system of extraction



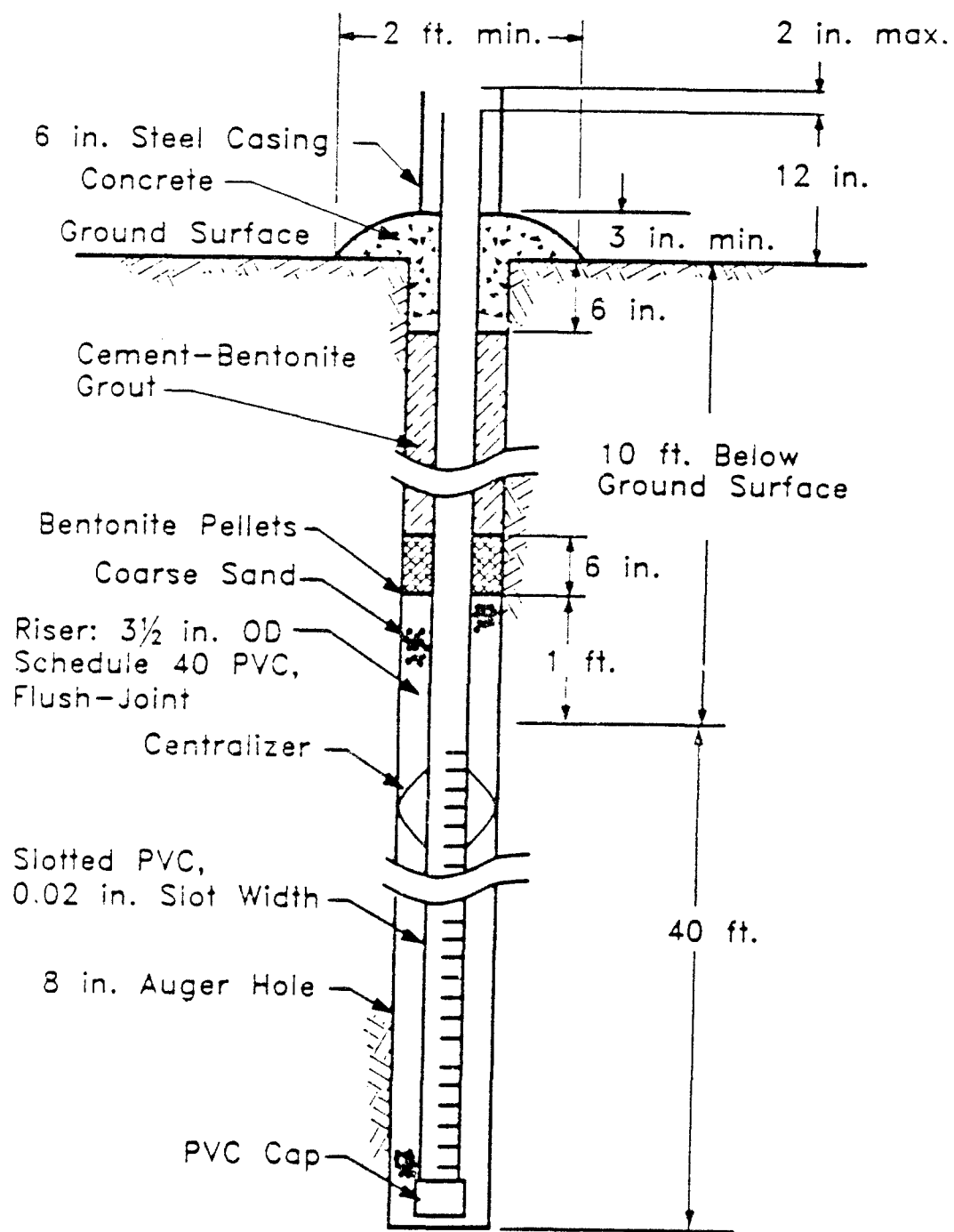


Figure 24. Detail of Vent Well Installation.

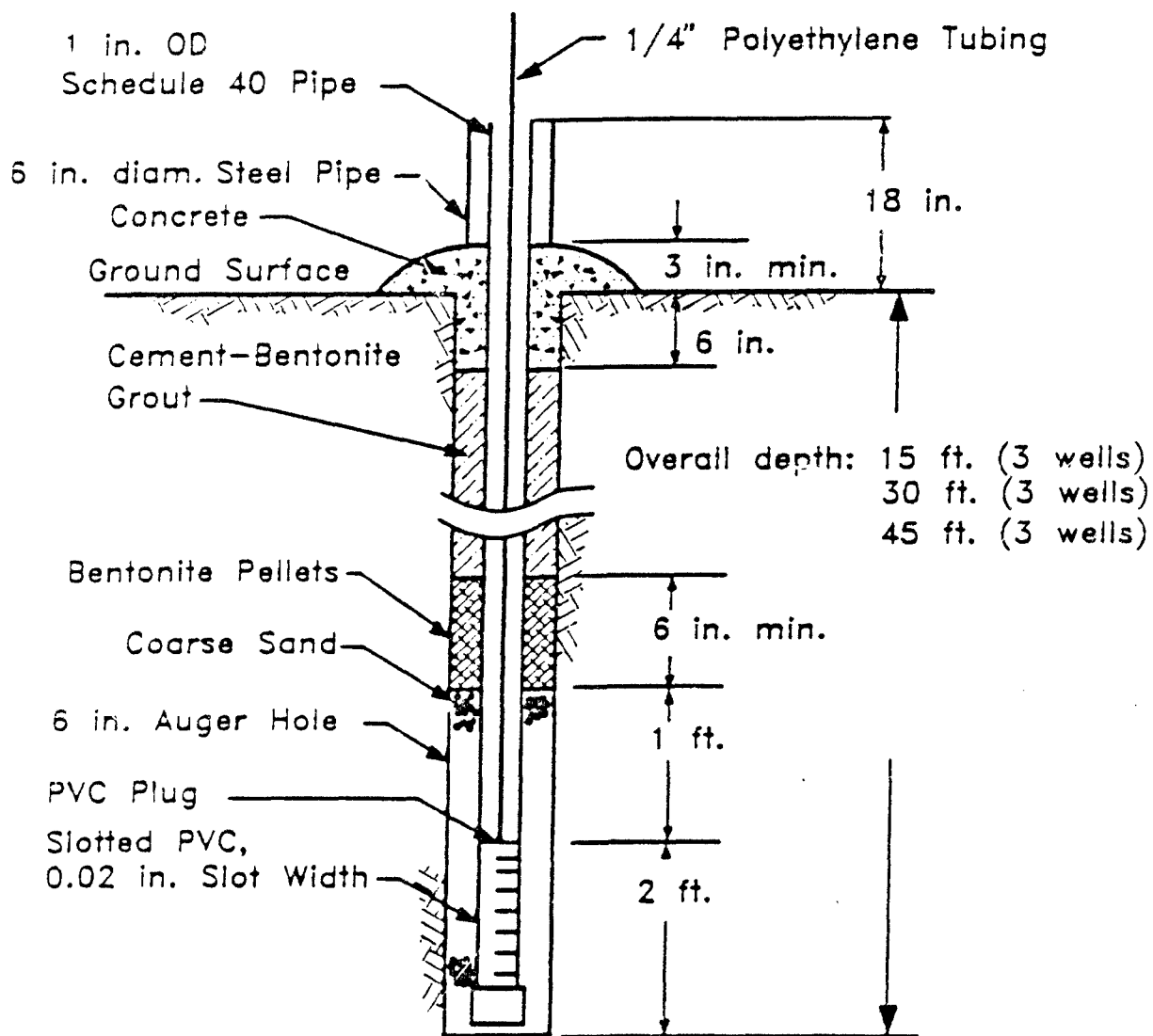


Figure 25. Vapor/Pressure Monitoring Well Installation.

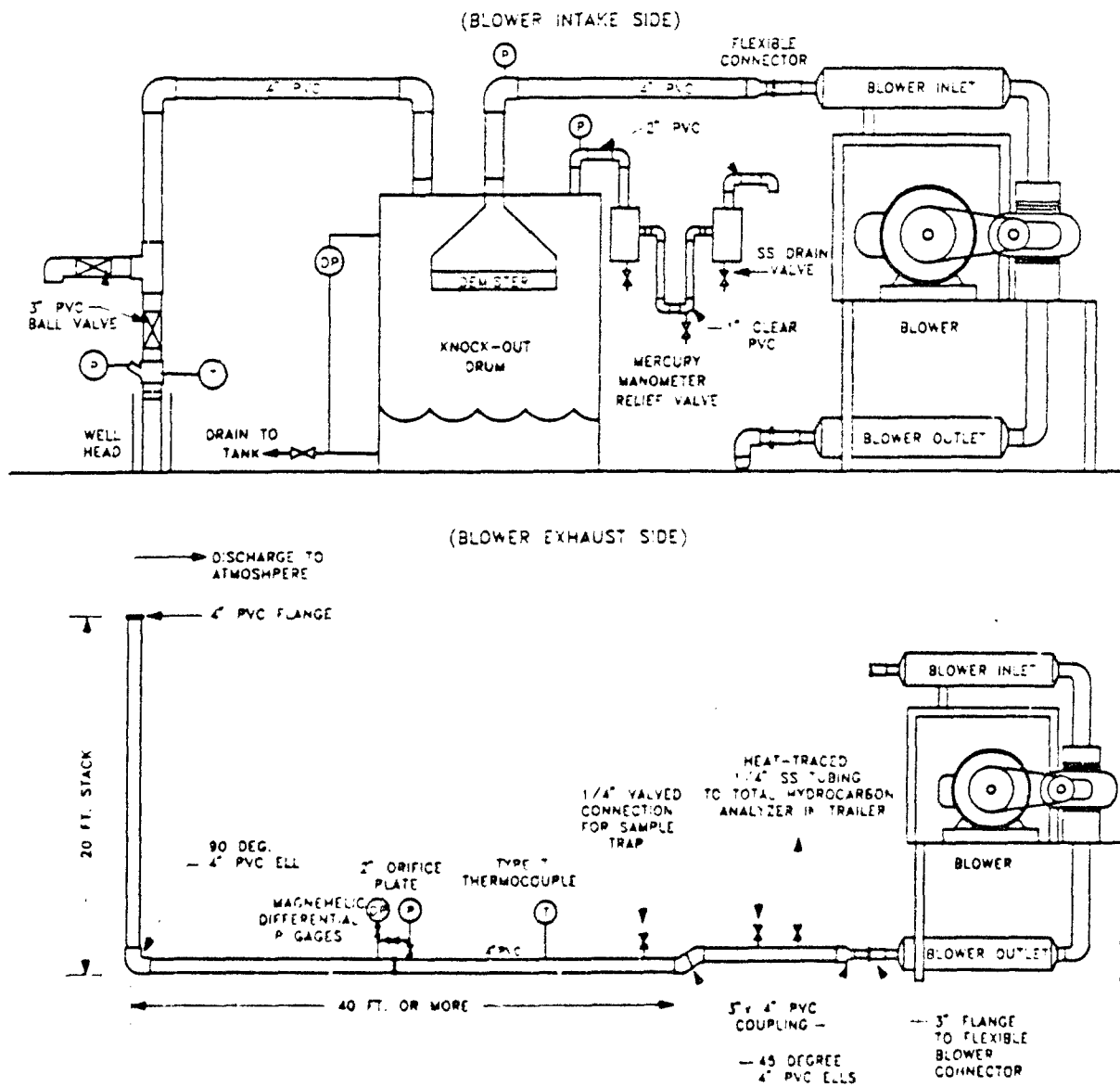


Figure 26. *In Situ* Soil Venting Single-Vent Test System.

gas at the end of operation. The line from the other tee connection was expanded to 4-inch (10.2-cm) PVC from the valve to minimize pressure drop. The 4-inch PVC pipe was taken through two 4-inch 90 degree PVC elbows before connection to the knock-out drum.

(2) **Knock-Out Drum.** A knock-out drum was installed upstream of the blower to protect the blower from suspended particles or water. The knock-out drum was constructed from a 208-liter (55-gallon) stainless steel drum. Connections were provided for inlet and outlet air streams, pressure taps, vacuum relief valve, and water drain. A modified stainless steel drum lid allowed all necessary connections. The drum lid was reinforced to withstand the vacuum generated during operation and to support all connections made through it. Inlet and outlet air connections on the drum lid were 4-inch (10.2-cm) threaded stainless steel pipe for connection with the 4-inch PVC lines. The inlet line was placed near the outside of the drum lid and the outlet line was centered. A mercury manometer/vacuum relief valve was connected to a 2-inch (5.1-cm) pipe fitting on the lid.

A demister was installed at the outlet from the drum to remove suspended water from the air stream to protect the blower. The demister was a 14.5-inch x 14.5-inch x 6-inch (36.8-cm x 36.8-cm x 15.2-cm) block of fiberglass and wire mesh, connected under the drum lid by a metal cone attached to the outlet pipe connection.

The knock-out drum was tested to a vacuum of 160 inches of water (40,000 Pascals). Nevertheless, a relief valve was installed to protect the drum from collapsing due to high vacuum from loss of flow. The relief valve was a mercury-filled U-tube, 1 inch (2.54 cm) in diameter, which was sized to blow through at a vacuum of 122 inches of water (30,400 Pascals). Catch pots were included on each leg to prevent the 120 mL of mercury from escaping into the drum or the environment.

(3) **Blower.** A rotary lobe positive displacement blower was used for the generation of vacuum. The blower was rated for 50 to 250 cfm (0.024 to 0.118 m<sup>3</sup>/second) of air flow at 80 inches of water (19,900 Pascals) vacuum, with a maximum capability of 122 inches of water (30,400 Pascals vacuum). The lobes and housing of the blower were constructed of aluminum to prevent sparking.

The blower was driven by a 7.5 horsepower (hp) (5600 Watt) explosion-proof electric motor, connected by a V-belt drive. Control of the motor over its range of 600 to 1750 rpm was achieved with a variable frequency controller. Electrical power (230 volts, three-phase, 60 cycle) was required. Since the frequency controller was not explosion-proof it was housed in the instrument trailer which contained an explosive gas monitor. Connections to the blower were made to the 4-inch (10.2-cm) PVC lines by a 4- to 3-inch (10.2- to 7.62-cm) PVC reducer and reinforced flexible connectors with 3-inch (7.62-cm) flanges.

Taps for the sample line to the THA were made near the outlet of the blower. Pipe-to-tubing fittings were threaded through the pipe wall for connection of 1/4-inch (0.64-cm) heat-traced stainless steel tubing running to and from the instrument trailer. A bypass stream from the hydrocarbon analyzer was injected into the air stream 2 feet (0.6 meter) down stream from the extraction tap.

Air flow rate was measured by a 2.00-inch (50.8-mm) orifice plate in the 4-inch (10.2-cm) pipe. The 0.120-inch (3.05-mm) thick stainless steel orifice plate was held in place by two 4-inch (10.2-cm) PVC flanges. The orifice plate was placed 20 feet (6.1 meters) downstream from

the hydrocarbon analyzer taps and 20 feet (6.1 meters) upstream of the 90 degree elbow before the stack. This allowed at least 60 pipe diameters upstream and downstream of any stream disturbance. Pressure taps for measuring pressure differential across the orifice plate were placed 4 inches (102 mm) upstream and 2 inches (51 mm) downstream of the orifice plate. Connections from the differential pressure gauges to the taps were valved to allow quick changes to pressure gauges of different ranges.

(4) Discharge. Discharge from the blower passed through a 4-inch (10.2-cm) PVC line, which was run along the ground 40 feet (12.2 meters) to a 20-foot (6.1-meter) stack. In the discharge section, effluent gas samples were taken, total hydrocarbon concentrations were monitored, and the air flow rate was measured.

### c. Analytical Trailer

A specially-outfitted fifth-wheel trailer, heated by electrical resistance space heaters, was used at the site to house the following equipment:

- explosive gas monitor,
- total hydrocarbon analyzer, and
- electrical connections blower motor controls.

(1) Explosive Gas Monitor. An MSA Series 510 Combustible Gas Detection System with four remote catalytic sensing heads was installed in the trailer for protection from buildup of potentially explosive gas mixtures in the trailer or in the air in the venting area.

The system was designed to have two sensing heads mounted in the trailer, one near the ceiling and one near the floor, to detect explosive gases both lighter and heavier than air. Another sensing head was to be plumbed into the exhaust gas line for continuous readings of the extraction gas. However, electrical problems with the detector rendered two of the circuits unusable during the pilot test. The two remaining sensing heads were employed as described below to ensure safe operation.

One sensing head was mounted in the center of the trailer near the instrumentation. Alarm signals from this detector would have shut down all 110 volt service in the trailer, and, subsequently, shut down power to the blower.

The other sensing head was mounted on a mobile stand and placed near the blower. An alarm signal from this detector would have indicated potentially hazardous levels in the air in the field and would have activated a relay shutting down power to the blower.

(2) Total Hydrocarbon Analyzer (THA). A Beckman Industrial Model 400A continuous THA with an FID was housed in the trailer for analysis of extraction gas. This analyzer is rated for a maximum full-scale concentration of 10 percent (100,000 ppmv) of methane. A sample side stream was pulled into the trailer through the heat-traced copper sample lines to the analyzer; the majority of the stream was returned to the venting system in a bypass line. The sample was fully oxidized inside the analyzer, with the exhaust vented by a tube to the outside of the trailer.

The hydrocarbon analyzer requires about 300 mL/minute of zero-grade air and about 80 mL/minute of mixed fuel (40 percent hydrogen, 60 percent nitrogen). The zero-grade air was supplied from Size 2 cylinders held in racks in the trailer. The hydrogen/nitrogen mixed fuel was held in Size 2 cylinders tied to the outside of the trailer. A pressure regulator set at 30 psig (207,000 Pascals) and a 50-psig (345,000-Pascals) relief valve, venting to the outside air, were placed on the fuel line outside the trailer to protect from overpressure and buildup of fuel inside the trailer. As an additional safety measure, a capillary was placed on the fuel line to limit fuel flow to approximately 5 standard ft<sup>3</sup>/hour ( $3.9 \times 10^{-5}$  m<sup>3</sup>/second).

(3) Electrical Connections/Blower Motor Controls. The electrical connections, including controls for the blower motor, were mounted on an instrument panel housed in the front section of the trailer. Electrical power (230 volt, 3 phase) was run from a building in the area and connected to the starter. The starter contained two switches: a hand switch for manual shutdown of the power and a 110-volt relay. The relay would shut off power if 110-volt service was shut down or if the alarm circuit from the combustible gas monitor was activated.

Single phase electrical power (110 volt, 50 amperes maximum) was run from lines in the area to a relay on the instrument panel. This relay was controlled by two alarm circuits from the combustible gas analyzer. An alarm signal to this relay would shut down all power. The line from the relay ran outside the trailer to the external power connection for the trailer.

## 2. Single-Vent Test System Operation

Operation of the single-vent test system included four runs in which the system was operated until it reached steady-state conditions, and an extended operation run. The system pressure was monitored periodically for measurement of transient response.

Before the steady-state runs, the blower was operated for approximately 10 minutes to determine the blower speed required to reach the desired flow rates of 50, 150, 200, and 250 scfm (0.024, 0.071, 0.094, and 0.118 standard m<sup>3</sup>/second). Due to the vacuum levels required and the altitude, actual flow rates were approximately 62, 124, 160 and 200 scfm (0.029, 0.059, 0.080, and 0.094 standard m<sup>3</sup>/second). Vacuum at each pressure monitoring vent was noted to determine if gauges of the proper ranges were installed. The blower was shut down and the system was allowed to recover for at least 15 minutes before commencement of the test. During the single-vent pilot test, the total hydrocarbon analyzer was calibrated using 0.70 mg methane/liter of gas (981 ppmv methane gas) standard (unlike the full-scale demonstration which used a hexane standard) and the combustible gas analyzer was tested with 29 percent LEL propane gas standard prior to operation.

Operating time for each run was noted from the point the blower was turned on. Vacuum measurements from each pressure monitoring vent and orifice pressure drop were recorded at 1, 5, 10, 15, 20, 25, 30, 40, 50, and 60 minutes, and every 15 minutes thereafter. Temperature at the vent head and blower exit were recorded periodically throughout. The system was operated at least until steady-state was achieved, determined by changes of less than 3 percent in all vacuum readings over a 15-minute interval. The system was purged for 5 minutes before shutting the blower off by opening the valve to atmosphere at the tee above the vent head and closing the valve at the vent head.

The extended run was operated at an extraction gas flow rate of approximately 205 scfm (0.097 standard m<sup>3</sup>/second) for approximately 8 hours. System parameters were recorded every 30 minutes for the duration of this run.

### 3. Single-Vent Test Results

Table 7 shows the operating flow rates and elapsed times of the ISSV system experiments. Five vent tests were run, ranging from 62 to 205 scfm (0.029 to 0.097 standard m<sup>3</sup>/second) air flow rate, for a total operating time of 19.6 hours. As described above, the first four tests were run to determine steady-state pressure distributions at each flow rate, with the final test used to determine system behavior with extended operation. The extended run was terminated to remain below emissions restrictions, based upon information provided by the THA. A total of 5,600 standard m<sup>3</sup> of gas was discharged. During each run, at least one gas sample was taken in a sample trap and the gas was continuously monitored by the THA.

TABLE 7. ISSV PILOT TEST CONDITIONS

DATE	FLOW RATE (standard m <sup>3</sup> /s)	TEST LENGTH (minutes)	DISCHARGE GAS VOLUME (m <sup>3</sup> )
1-18-88	0.029	157	276
1-19-88	0.059	122	428
1-19-88	0.094	131	742
1-20-88	0.080	279	1335
1-20-88	0.097	486	2821

#### a. Pressure Results

The pressure monitoring vents were positioned and labelled as shown in Figure 23. Assuming homogeneous soil and a constant flow distribution, this array allows an estimate of vertical and lateral pressure distributions in the soil surrounding the extraction vent.

Pressures at each monitoring vent were measured by Magnehelic differential pressure gauges and U-tube manometers. The U-tube manometers were filled with a 50/50 mix of ethylene glycol and water to prevent freezing. Agreement of the measurements from the U-tube manometers and the Magnehelic gauges was determined to be within the readability of the instruments.

Transient pressure results for the extraction and monitoring vents are shown in Figures 27 through 29. Results were not obtained for Monitoring Vent 3, which did not exhibit measurable vacuum and was believed to be plugged by grout during installation. The results show that the response of the system was extremely fast as would be expected in highly permeable soil, reaching steady state within 90 minutes in each case.

Steady-state pressure distribution results from each test are shown in Table 8. The data indicate a large pressure drop in the high flux area near the extraction vent, tailing off exponentially with radial distance. Higher vacuum readings at the lower depths is due to a vertical component of air flow, indicating that some air flow was possible through the icy soil surface.

The data shown in Table 8 are also presented as pressure contour maps in Figure 30. This means of displaying the data is only applicable for homogeneous soils with uniform air flow distribution. This assumption appears valid except for the results obtained from MW5 at 20 feet (6.1 meters) distance and 30 feet (9.1 meters) depth. Possible causes of this inconsistency are heterogeneous soil, or a leak in the pressure monitoring line. The results for MW5 were not included in the contours. Since the air flow direction is perpendicular to the pressure contours and its magnitude is inversely proportional to the distance between contours, the contours give an indication of the air flow patterns in each test. The effect of some air flow from the surface may be seen, as well as the lesser magnitude of air flow deeper in the soil and farther from the vent.

#### **b. Extraction Vent Pressure Drop**

A pressure gauge was connected to a 1/4-inch (0.64-cm) line which was lowered to several points in the 3-inch (7.62-cm) extraction vent during steady-state operation. This allowed measurement of the pressure drop in the extraction vent at each flow rate. Results are shown in Table 9. These results indicate that the pressure drop of flow in the extraction vent can become considerable at higher flow rates, causing a nonuniform vacuum with depth and higher vacuum levels necessary to induce flow. It was determined necessary to use vent pipe with a diameter larger than 3 inches (7.62 cm) to operate at flow rates much larger than 250 scfm (0.118 standard m<sup>3</sup>/second), without excessive head loss.

#### **c. Vacuum Requirements**

The vacuum required for soil gas extraction rates with the vent design used is shown in Figure 31. The results are nearly linear, which agrees with some flow models predicting linear behavior up to about 100 inches of water (24,900 Pascals) vacuum. However, this does not agree with the USATHAMA results (Reference 5), which showed a geometric relationship. Extrapolation of the curve to higher flows is therefore somewhat uncertain, but it is definite that relatively high flows are possible with low power requirements.

#### **d. Extracted Gas Concentration Results**

The extracted gas concentration was measured by two means: (1) real-time analysis by a THA and (2) grab samples taken on traps for GC analyses. The average THA readings during each test and GC sample numbers are shown in Table 10.



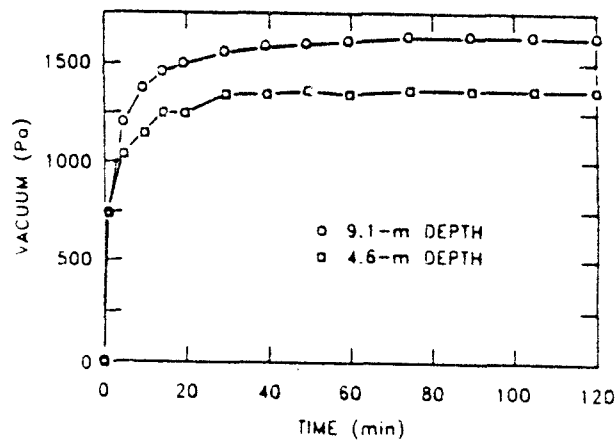


Figure 27. Transient Pressure Response - Single Vent Test, Extraction Rate - 0.094 Standard  $\text{m}^3/\text{Second}$ , Monitoring Point Distance - 3.0 meters.

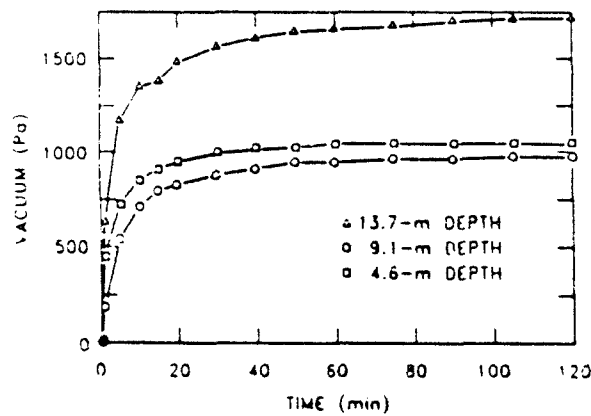


Figure 28. Transient Pressure Response - Single Vent Test, Extraction Rate - 0.094 Standard  $\text{m}^3/\text{Second}$ , Monitoring Point Distance - 6.1 Meters.

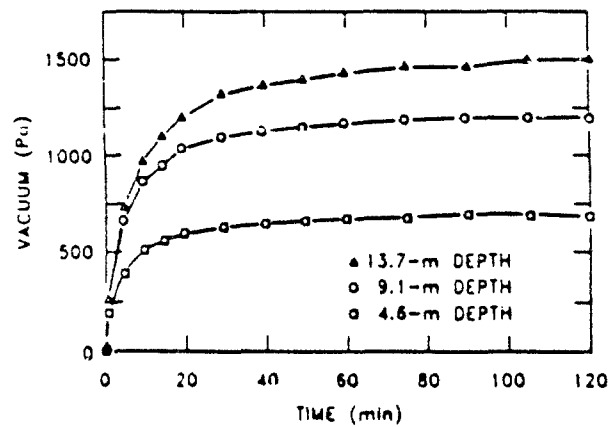


Figure 29. Transient Pressure Response - Single Vent Test, Extraction Rate - 0.094 Standard  $\text{m}^3/\text{Second}$ , Monitoring Point Distance - 9.1 Meters.

TABLE 8. SINGLE VENT TEST VACUUM DISTRIBUTIONS

EXTRACTION RATE (standard m <sup>3</sup> /second)	DEPTH (meters)	STEADY-STATE VACUUM (Pascals)			
		0*	3.1	6.1	9.1
0.029	0.0	1369			
	4.6		398	361	229
	9.1		597	306	426
	13.7			622	498
0.059	0.0	2737			
	4.6	2488	846	647	388
	9.1	2389	1040	545	699
	13.7	2339		1010	886
0.080	0.0	4106			
	4.6	3459	1120	871	530
	9.1	3285	1369	761	933
	13.7	3185		1321	1182
0.094	0.0	4977			
	4.6	4181	1369	1045	654
	9.1	3932	1630	918	1120
	13.7	3782		1603	1401

\*Distance of pressure monitoring point from extraction vent in meters.

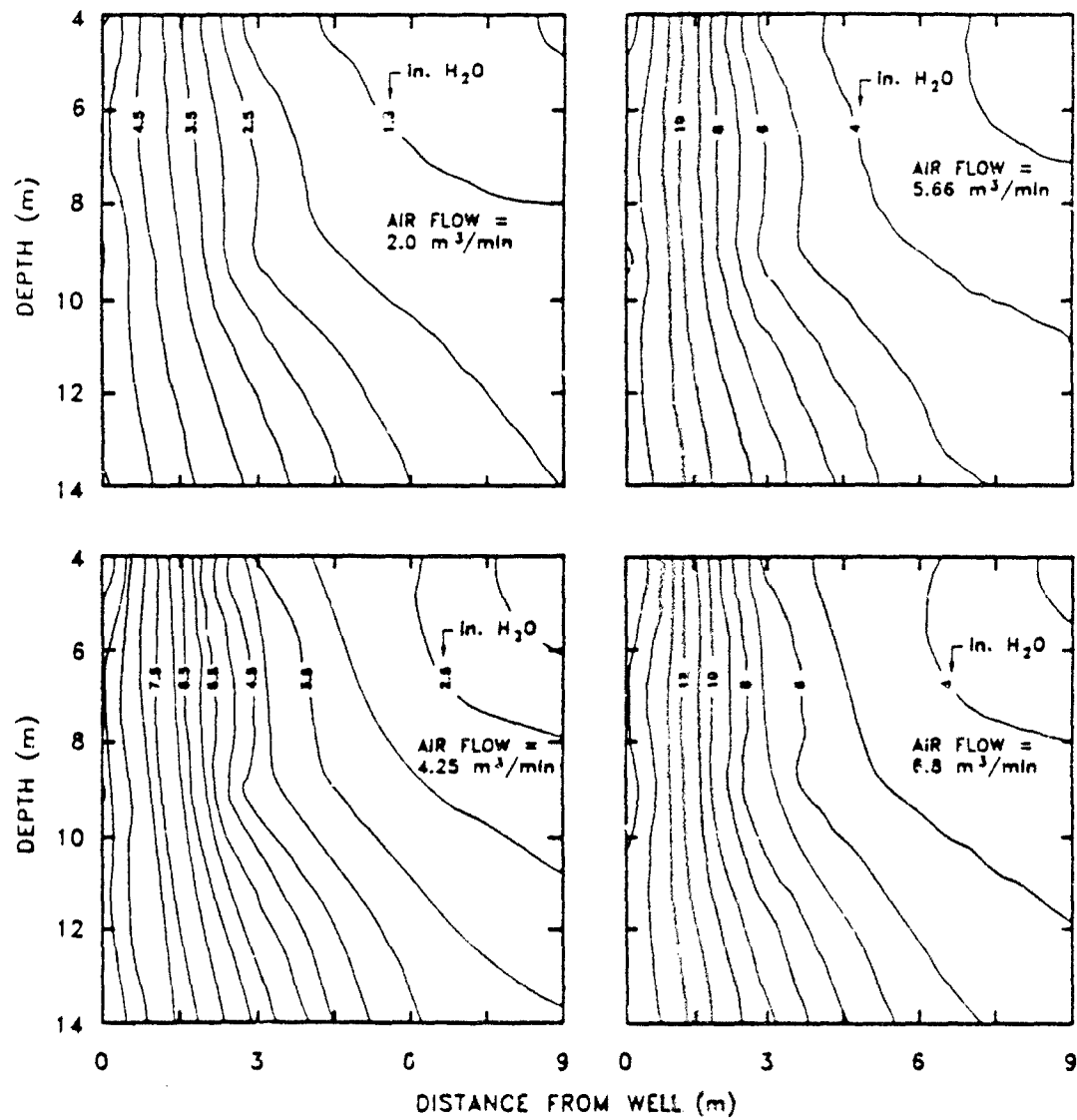


Figure 30. Pressure Contours During Pilot Test.

TABLE 9. EXTRACTION VENT PRESSURE DROP

DEPTH (meters)	VACUUM IN PASCALS		
	0.059* (standard m <sup>3</sup> /second)	0.080 (standard m <sup>3</sup> /second)	0.094 (standard m <sup>3</sup> /second)
0.0	2936	4156	4728
1.5	2687	3882	4604
3.0	2638	3782	4454
4.6	2488	3459	4181
6.1	2439	3384	4031
7.6	2414	3310	3957
9.1	2389	3285	3932
10.7	2389	3235	3882
12.2	2364	3210	3807
13.7	2339	3185	3782
15.2	2339	3160	3757

\*Extraction flow rate.

(1) THA Results. The extraction gas hydrocarbon concentrations, as measured by the THA, were found to be very uniform during each run. For all runs, readings ranged from 0.079 to 0.093 grams/liter as methane. Using a relative weight response in an FID of 1 to 0.8 (weight hydrocarbons to the weight of methane) this corresponds to a concentration of 0.063 to 0.074 grams/liter hydrocarbons in the gas stream. Assuming that the concentration of hydrocarbons was constant during each short test period, 5600 standard m<sup>3</sup> of gas would have discharged 772 to 911 pounds (350 to 413 kg) of hydrocarbons. Therefore, using the real-time THA information, the test was terminated early to remain below emissions limits.

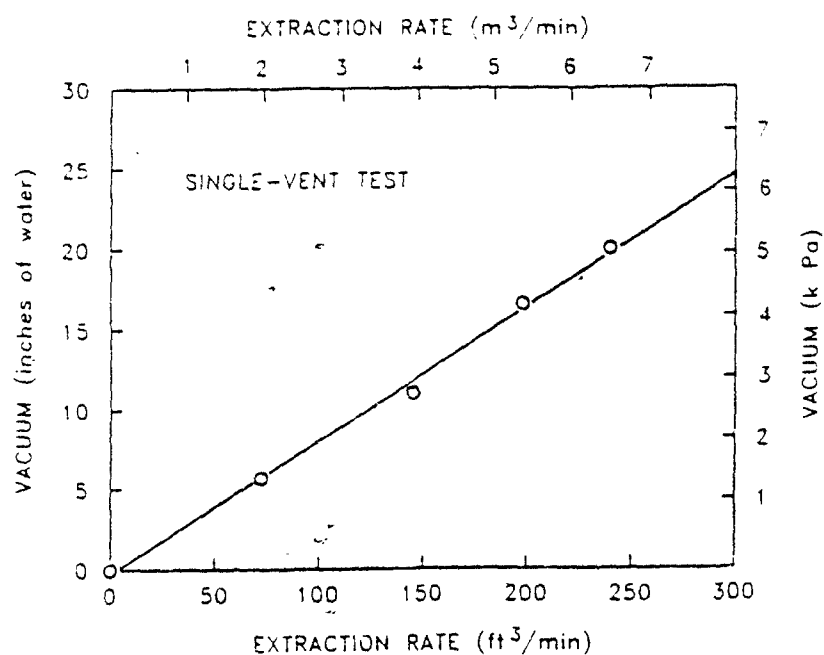


Figure 31. Single Vent Test Vacuum Requirements.

TABLE 10. SUMMARY OF GAS SAMPLING CONDITIONS

DATE	FLOW RATE (standard m³/second)	GC SAMPLE	AVERAGE THA READING (ppm as CH <sub>4</sub> )
18 Jan 88	0.029	70CFM-1	84,500*
19 Jan 88	0.059	150CFM-1	116,000
19 Jan 88	0.094	245CFM-1	126,000
19 Jan 88	0.094	245CFM-1	126,000
20 Jan 88	0.080	200CFM-1	131,000
20 Jan 88	0.097	250CFM-1	129,000

\*Value low due to ranging of instrument.

After completion of the single-vent test and analyses of the GC traps, an experiment was conducted to prove the performance of the THA as a simulation of the compounds encountered in the field. As seen in Figure 32, the FID becomes saturated above a level of 0.071 grams/liter methane equivalent, causing a large departure from the assumed linear response. Thus, the levels indicated by the THA in the field, upon which real-time emissions monitoring was based, were likely lower than the actual concentrations.

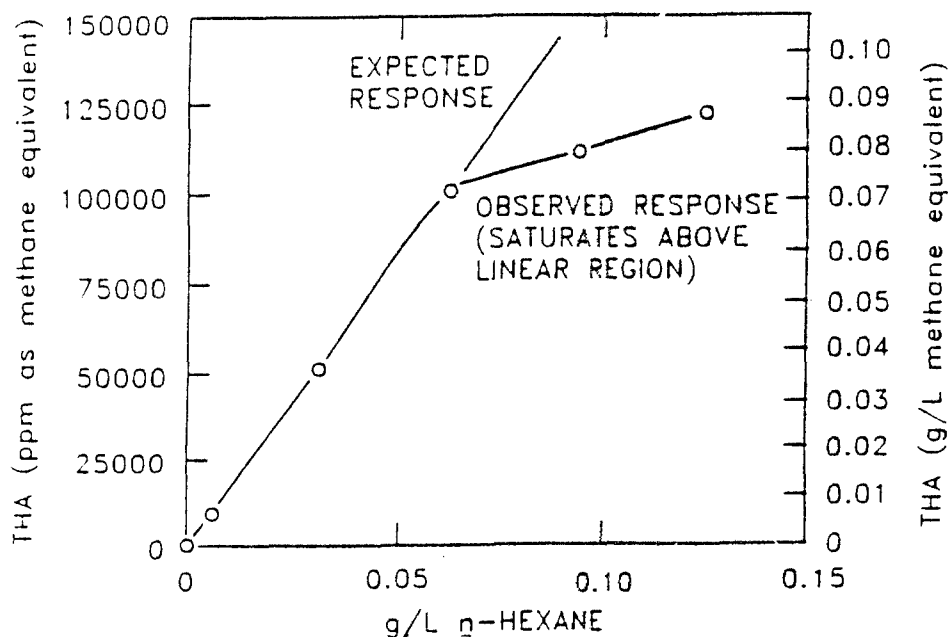


Figure 32. THA Response.

(2) GC Analyses. The GC analyses of the gas samples varied by a factor of 100, from 0.029 to 2.07 grams/liter, showing a wide scatter that was not evident from the THA during the runs and placing some uncertainty on the validity of the GC concentration results. The scatter in the results is believed to be due to condensed hydrocarbons entering the traps during sampling. The GC sample traps were connected to the system by a 1/4-inch (0.62-cm) valved tee downstream of the pump on the sampling line feeding the THA. The increased pressure [1.5 to 2 pounds/inch<sup>2</sup> gauge (10,300 to 13,800 Pascals)] as compared a slight vacuum in the extraction vent at this point would likely be sufficient to condense some water vapor and hydrocarbons on the exposed metal fittings. Although the valve was purged to remove visible amounts of condensation, only a microscopic quantity would be required to greatly disturb the analyses.

Typical analyses of new JP-4 at Hill AFB report an ASTM initial boiling point of the fuel as 58.9°C. A calculated equilibrium flash vaporization curve for the fuel indicates that it will behave much like n-hexane in vapor-liquid equilibrium. Comparison with the vapor pressure-temperature plot for n-hexane shows that the highest possible concentration of hydrocarbons from pure fuel at 12.8°C would be approximately 0.0285 pounds/ft<sup>3</sup> (0.46 grams/liter). This eliminates the

concentration values found for two of the GC samples (reading 0.878 and 2.072 grams/liter), since the gas sampled came from vapor in contact with JP-4 or JP-4 depleted of light fractions. As discussed above, it is likely that the high values are due to entrained condensation entering the sample traps.

Accepting the values for the samples below 0.46 grams/liter (those reading 0.397, 0.441, 0.266 and 0.029 grams/liter), yields a flow-weighted average concentration of 0.204 grams/liter, for an estimated discharge of 2495 pounds (1,132 kg) of hydrocarbons. This is considered a maximum estimate because of the uncertainties due to condensation.

#### e. Calculation of Best Estimate of Emissions

The relative hydrocarbon weight fractions in each gas sample are shown in Table 11. Unlike the concentration values, the data are very consistent, showing a depletion of the light fractions as the process continued. These consistent data provide adequate information for making a conservative estimate of emissions.

For the estimate of emissions, it is assumed that the hydrocarbons in the extraction gas are in equilibrium with the liquid hydrocarbons in the ground. From the relative amounts of hydrocarbons in each hydrocarbon range in the gas samples shown in Table 11, the relative mole fractions of each range in the liquid in the soil were calculated using vapor-liquid equilibrium K-values. Since the hydrocarbon mole fractions in the liquid must sum to 1, the actual liquid mole fractions may be calculated and an equilibrium concentration in the gas may then be calculated using Raoult's Law.

Calculated gas concentrations are shown in Table 12. These values show a decrease from an approximate initial concentration of 0.25 grams/liter to a final value of 0.015 grams/liter. A flow-weighted average of these concentration results yield an emissions estimate of approximately 1329 pounds (600 kg) of hydrocarbons. This is about one-half of the estimate based directly on the gas analyses, and is roughly consistent with the THA analyses. The equilibrium method is considered to be conservatively high; the method does not consider the heavy hydrocarbons present in the liquid which would decrease the equilibrium concentration of lighter hydrocarbons in the gas phase according to Raoult's Law. The assumption of equilibrium between the gas and liquid phases will also tend to overestimate the concentration of hydrocarbons in the gas phase.

### C. COLUMN TEST

#### 1. Materials and Method

Cuttings from the boring of the extraction vent were collected, sealed in a 55-gallon (208-liter) stainless steel drum, and delivered to ORNL for testing. Approximately 6 inches (15 cm) of head space existed in the drum.

A 21-pound (9.54-kg) soil sample was removed from the drum, weighed, and placed in a 5-inch (12.7-cm) inside diameter glass column, suspended by stainless steel screens. All transfer operations were performed with the soil enclosed in plastic to minimize contact of the soil with air. The soil column was compacted by vibration overnight.

TABLE 11. HYDROCARBON WEIGHT FRACTIONS IN GAS SAMPLES

HYDROCARBON RANGE	WEIGHT FRACTION OF HYDROCARBONS					
	218 <sup>a</sup>	576	1184	1354	2188	5549
C4-C5	0.092	0.101	0.083	0.009	0.023	0.002
C5-C6	0.345	0.379	0.354	0.353	0.122	0.039
C6-C7	0.331	0.317	0.339	0.379	0.188	0.086
C7-C8	0.180	0.144	0.167	0.184	0.269	0.078
C8-C9	0.042	0.045	0.049	0.057	0.230	0.191
C9-C10	0.009	0.013	0.008	0.015	0.120	0.335
C10-C11	0.001	0.001	0.001	0.002	0.042	0.215
C11-C12	0.000	0.000	0.000	0.000	0.005	0.046
C12-C13	0.000	0.000	0.000	0.000	0.000	0.005
C13-C14	0.000	0.000	0.000	0.000	0.000	0.001
C14-	0.000	0.000	0.000	0.000	0.000	0.001

<sup>a</sup>Standard cubic meters of gas extracted prior to sampling.

TABLE 12. CALCULATED EXTRACTION GAS CONCENTRATIONS

VOLUME OF AIR EXTRACTED (standard m <sup>3</sup> )	CALCULATED HYDROCARBON CONCENTRATION (grams/liter)	CALCULATED MASS OF HYDROCARBONS (kg)
218	0.245	62.6
576	0.246	102.5
1184	0.246	174.6
1354	0.243	48.5
2188	0.028	132.0
5549	0.014	82.6
		TOTAL = 602.8



A small hydrocarbon vapor sampling pump was used to induce air flow through the soil column. Air entering the soil from the top of the column passed through a water bubbler to prevent drying of the soil. A 0- to 1.7-liters/minute rotameter was used to measure flow rate, and Magnehelic differential pressure gauges were used to measure pressure drop across the column. Flow from the sampling pump was sent through a Beckman Industrial Model 400A THA, and calibrated with 10 percent methane. All lines were 1/4-inch (0.64-cm) polyethylene tubing.

The 0.0047-m<sup>3</sup> soil column was vented for 6.1 hours at 0.5 liters/minute, with the column effluent concentration continuously recorded.

## 2. Column Test Results

Effluent concentrations from the column test are shown later in Figure 38. These concentrations are displayed in terms of scaled time, which is defined as the amount of air passed through the column divided by the bed volume. Effluent concentrations were initially much lower than those encountered during the single-vent pilot test. This is likely due to loss of light-weight hydrocarbon fractions from the soil sample during collection and transport.

The column effluent concentration increased slightly in the early stages of the test after the air volume in the lines between the column and the analyzer was purged. The concentration then peaked and began to decrease rapidly. This drop of concentration in the column test forms a straight line in a log-log plot, as do the results of several field tests reported in the literature (see Volume I). However, it is doubtful that a simple column test can be constructed that would provide reliable system behavior projections. This is due mainly to differences in air flow/contaminant contact; collection of a representative sample would also be a factor.

## D. *IN SITU* PERMEABILITY TESTS

The air permeability,  $k$ , of the soil is the single most important site variable needed for design of a soil venting system. Values for the air permeability are necessary for estimation of the quantity and spatial distribution of air flow as well as vacuum and power requirements of blowers. To assess spatial variability of air permeability at the spill site, tests were conducted on each of the monitoring wells used in the pilot test. In addition, a simple and inexpensive procedure was developed for determining the air permeability in an open borehole using inflatable packers. Two additional air permeability measurements were made using this procedure.

### 1. Transient Recovery Procedure

#### a. Methodology

Air permeability tests require the creation of a pressure stress by either injecting or withdrawing air. A large pressure drop occurs along small diameter tubing, such as the 0.64-cm diameter tubing used in the pressure monitoring wells (see Figure 25). As a result it was not possible to measure downhole pressure during the injection or withdrawal of gas. Therefore, transient recovery tests were conducted. The tests were performed by injecting nitrogen at a known and constant rate until a steady-state pressure was obtained in the test interval. It was most convenient to inject gas from high pressure cylinders. After steady-state had been reached, the injection was shut off and pressure in the test interval could be accurately measured near the top of the well since

significant head loss no longer occurred. Because the transient response is short for shallow tests, a high-speed data logger and pressure transducer capable of collecting data at one-second intervals were used to record pressure as a function of time.

The general setup for the transient recovery tests in the monitoring wells is shown in Figure 33. The three-way valve shown in Figure 33 was included to protect the pressure transducer during injection against the high pressure which was required to obtain the necessary flow rate through the small diameter access tube. Flow rates during these tests were nominally 0.003 kg/second, requiring about 15 minutes to approach steady-state conditions.

#### **b. Data Interpretation**

The transient pressure response depends on the air permeability, flow rate, air-filled porosity, and on the geometry of the test. The air permeability from each transient recovery test was determined using a curve matching technique detailed in Volume II. Type curves generated using the finite-element flow model FEMAIR (see Appendix K, unpublished, available from ORNL and AFESC) with boundary conditions indicating the depth of the test intervals and including no-flow boundary at 50 foot depth (the depth of the perched water) were matched to the transient pressure response. The curve-matching procedure yields a result for the air permeability, but does not provide an accurate measure of the air-filled porosity.

#### **c. Results**

Figure 34 shows the pressure results and the fit to the type curve for monitoring well 34. Similar fits were obtained for all except monitoring well 37, which did not respond during the venting test and no nitrogen could be injected for determining air permeability. The well was presumed to be plugged. Calculated air permeabilities at the other pressure monitoring points ranged from  $3 \times 10^{-12}$  to  $6 \times 10^{-11} \text{ m}^2$ .

### **2. Steady State Procedure**

#### **a. Methodology**

In addition to air permeability tests on the existing monitoring wells, a simple procedure was developed for determining air permeability in shallow boreholes. The tests were made using the equipment shown in Figure 35. All of the components are commercially available. A hand-operated bucket auger was used to create the borehole. An inflatable packer provided a means of sealing the borehole from land surface down to the test interval. The pressure monitoring tube allowed accurate measurements of the pressure in the test interval, using a pressure gauge located at the surface. Since only pressure changes are used in the calculations, it was not necessary to correct the measurements for the weight of air inside the monitoring tube. Because significant head loss occurred along the air hose during injection, it was important to use a separate pressure monitoring tube. The purpose of the flowmeter was to assure that a constant flow rate occurred throughout the test. The absolute flow rate was determined by monitoring the source tank pressure, and, thus, it was not necessary to calibrate the flow meter for the temperature and pressure conditions of the test.

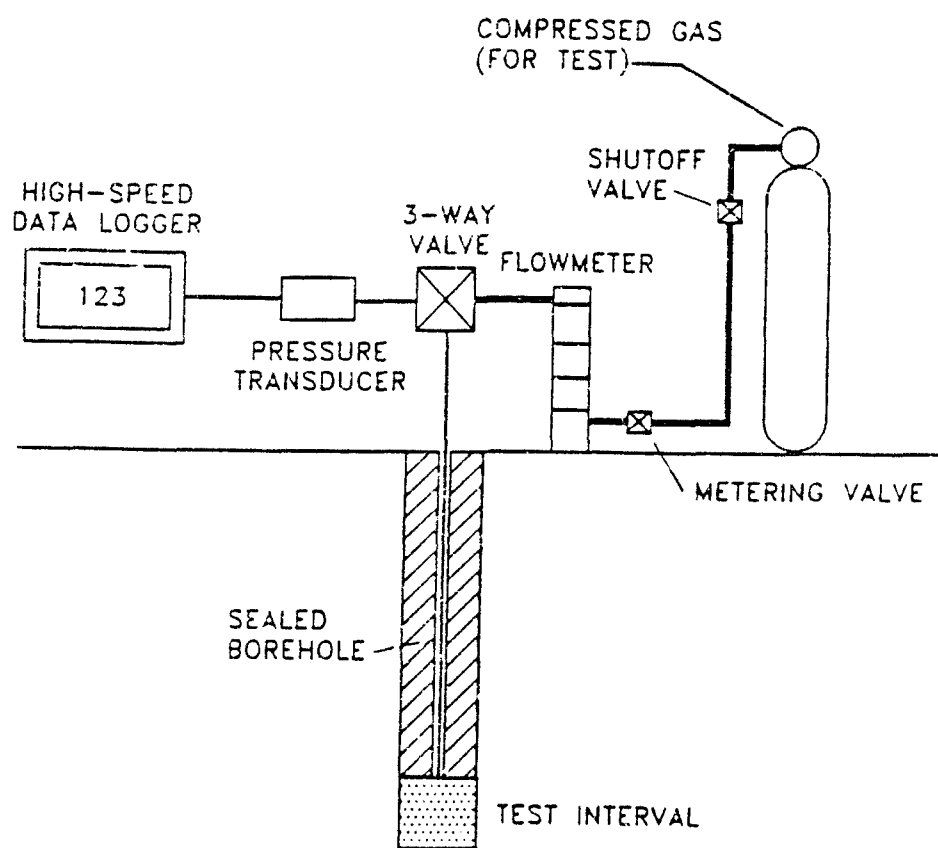


Figure 33. Schematic Diagram of Equipment and Installation Used to Conduct Transient Air Permeability Tests in Pilot Test Pressure Monitoring Wells.

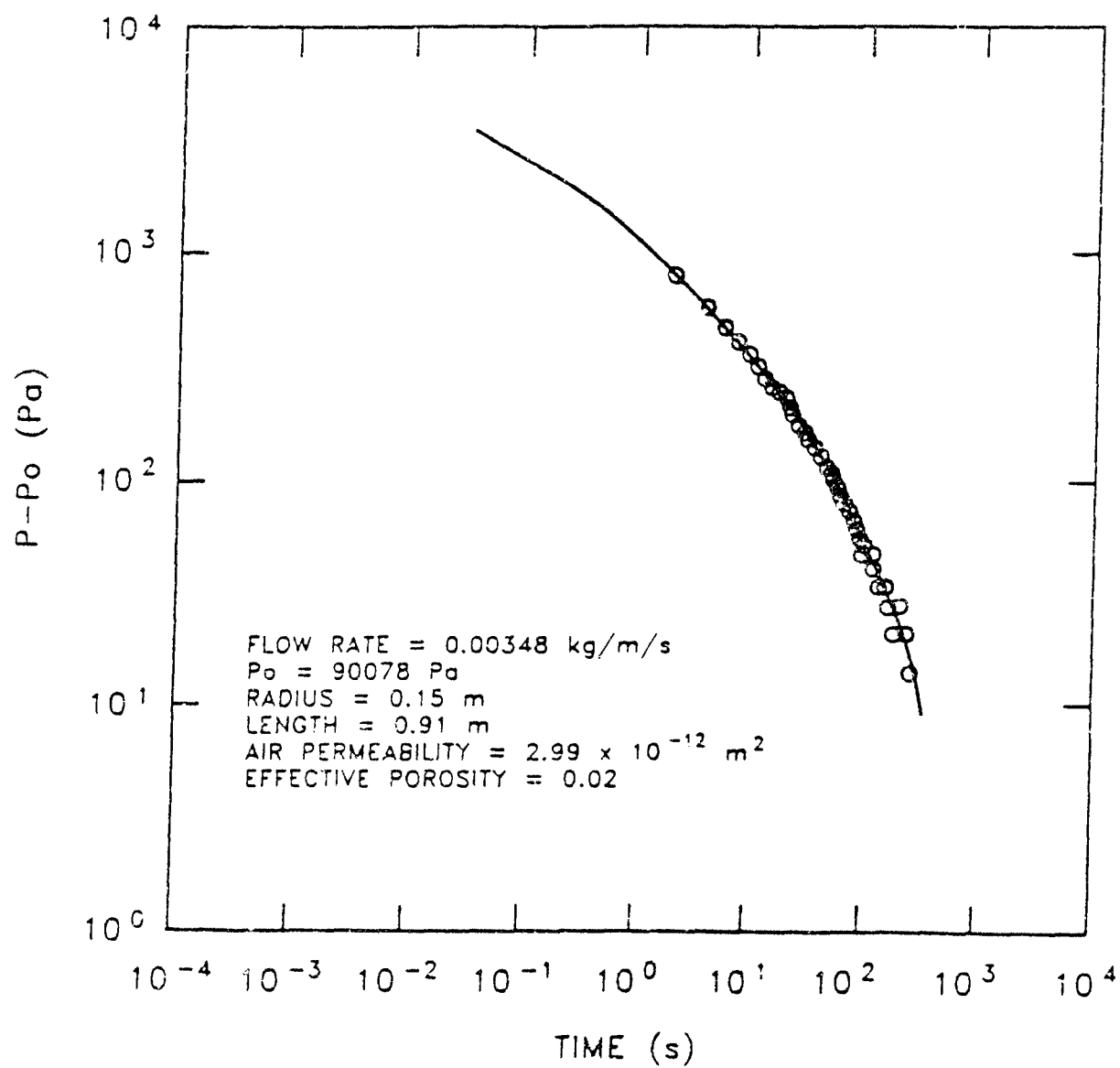


Figure 34. Transient Pressure Data and Fit to Type Curve for Test of Monitoring Well 34.

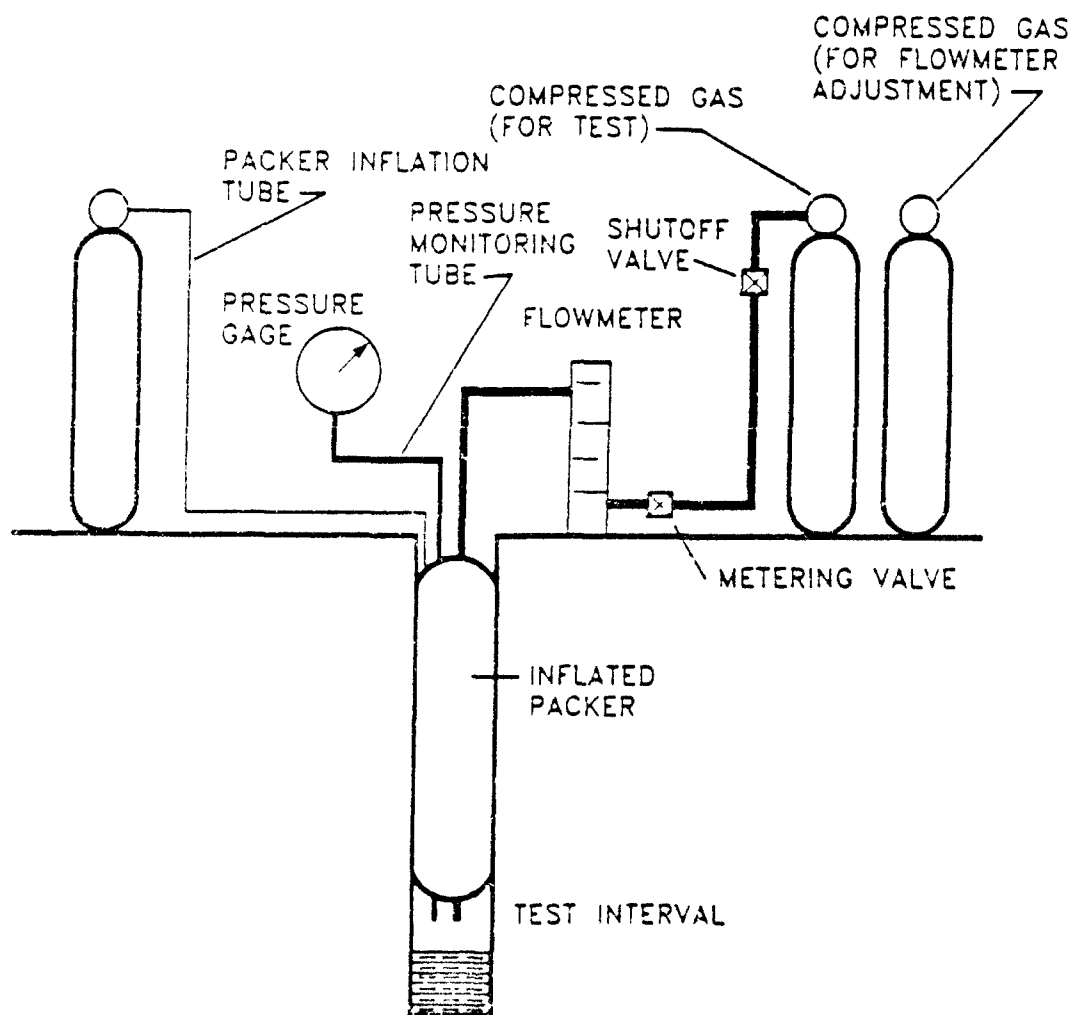


Figure 35. Schematic Diagram of Equipment and Installation Used to Conduct Steady-State Air Permeability Tests in Shallow Boreholes.

The optimal flow rate, and hence the required capacity of the flowmeter, depends on the permeability and the length of the test interval. The steady-state pressure change in the test interval was not allowed to exceed 14,000 Pascals to prevent invalidating the constant air density assumption. The optimal pressure drop is about 7,000 Pascals, which in these tests required a nominal flow rate of 0.004 kg/second.

Three compressed nitrogen cylinders were used for each test; one to inflate the packer, one to adjust the flow meter, and one to conduct the test. The packer was inflated to about 50 psig (345,000 Pascals). The flow rate was then adjusted to the optimal value by injecting nitrogen into the borehole from one of the compressed gas cylinders. The gas hose was then connected to the other compressed gas cylinder to conduct the test. The absolute flow rate was determined by the change in cylinder pressure over the time of the injection. The gas pressure is a function of temperature inside the cylinder, which changed during the test as a result of Joule-Thompson cooling. To eliminate this problem the cylinder pressure was measured before the test, and then sufficiently long after the test to allow the cylinder to warm to its initial temperature. The test was started by first closing the shutoff valve (without adjusting the metering valve), then opening the cylinder valve. The shutoff valve was then opened and a stopwatch started. The injection continued until a steady down-hole pressure was obtained.

#### **b. Results**

The air permeability value for each steady-state test was calculated using a type curve technique as described in Volume II.

Two tests were conducted using the steady-state packer method described above. Test intervals ranged from 0.6 to 1.4 meters BLS and yielded air permeabilities of  $1.7 \times 10^{-11}$  and  $3.7 \times 10^{-11} \text{ m}^2$ . These values are within the range of permeabilities measured during the transient tests.

### **3. Summary of In Situ Permeability Testing**

Four separate depth intervals were tested in the transient recovery tests and the steady-state packer tests. The data indicate the possibility of a low permeability zone at about 9 meters BLS. The variation of measured air permeability at each depth is less than a factor of 3 except for the 9-meter depth where the variation is nearly a factor of 10. This suggests that the low permeability zone may be discontinuous over the site. These permeability tests are in general agreement with the bulk value determined from the single-vent pilot test as described in the following section.

## **E. FLOW MODELING**

The pressure measurements and air flow data at the vent well were used to calibrate a two-dimensional, radially symmetric flow model. Once calibrated to the existing field conditions, the model served as a powerful illustrative tool for aid in designing the full-scale venting system. Furthermore, the calibrated model provided insight into the placement of monitoring wells to maximize the usefulness of field data.

The numerical code, FEMAIR, used in modeling air flow in soil is described in detail in Appendix K (unpublished, available from ORNL and AFESC). This appendix also presents the

output of several simulations showing the importance of vent design and placement upon air flow and soil cleanup. Modeling of the pilot test air flow is described below.

The first simulation of the pilot test was performed with an isotropic and homogeneous permeability and no surface barrier. The simulated air flux that resulted from the measured pressure distribution at the vent well was then integrated over the length of the well screen and compared with the observed air extraction rate. The air permeability was then scaled so that the integrated air flux along the vent screen agreed with the observed discharge. This procedure resulted in an air permeability of  $4.4 \times 10^{-11} \text{ m}^2$ .

Although only the pressure distribution at the vent well is required for determining the bulk effective air permeability, an evaluation of the mathematical model and the assumptions employed can be made by comparing the observed and modeled pressure distributions at various points in the solution domain. The initial simulations were done using a constant pressure boundary at land surface. Assuming radial symmetry, the observed pressure data were collapsed onto a plane for comparison with the model results. Figure 36 presents FEMAIR model outputs of isobars in the soil at an extraction rate of 0.059 standard  $\text{m}^3/\text{second}$ , superimposed on points designating results of the single vent test. The observed pressure in all of the pressure monitoring points was less than the simulated value.

A second simulation was conducted using a no-flow upper boundary simulating the effects of a perfect surface barrier. The pressure results of the second simulation are shown in Figure 37; however, with the perfect surface barrier, the pressure contours are more parallel to the vent pipe than the field measurements. The no-flow boundary produced a much better fit of the data. The difference between observed and computed pressures was less than 300 Pascals for most of the monitoring points. Although it is likely that a better fit could be obtained by using a variable permeability distribution and/or an imperfect surface barrier, the model was deemed adequate for aiding in the design of the full-scale test.

The cause of the improved fit of the model when a no-flow boundary at the surface was used can only be speculated. The test was conducted in January during cold weather. Site personnel were not able to install driven monitoring probes due to icy surface conditions. Frozen surface soils have been documented to inhibit the diffusive flux of carbon dioxide and oxygen in forested soils (Reference 12), and it is possible that a natural barrier existed. This has important implications to a full-scale venting since the radius of influence of a venting well increases significantly when a no-flow surface boundary is used.

## F. DISCUSSION

### 1. Projected System Behavior

Estimates of the removal performance of the soil venting system are useful for projecting the operating time required and for economizing the system design. However, uncertainties in the amount and distribution of contamination and component behavior make this prediction difficult.

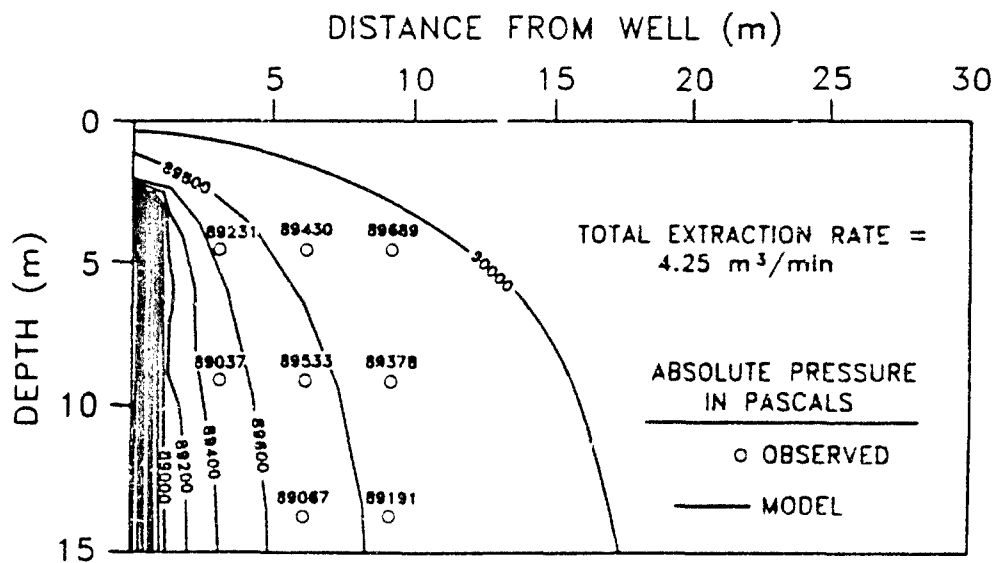


Figure 36. Comparison of Observed and Modeled Air Pressure in the Vicinity of the 4.25 m³/Minute Single-Vent Test With a Constant Pressure Boundary at Land Surface.

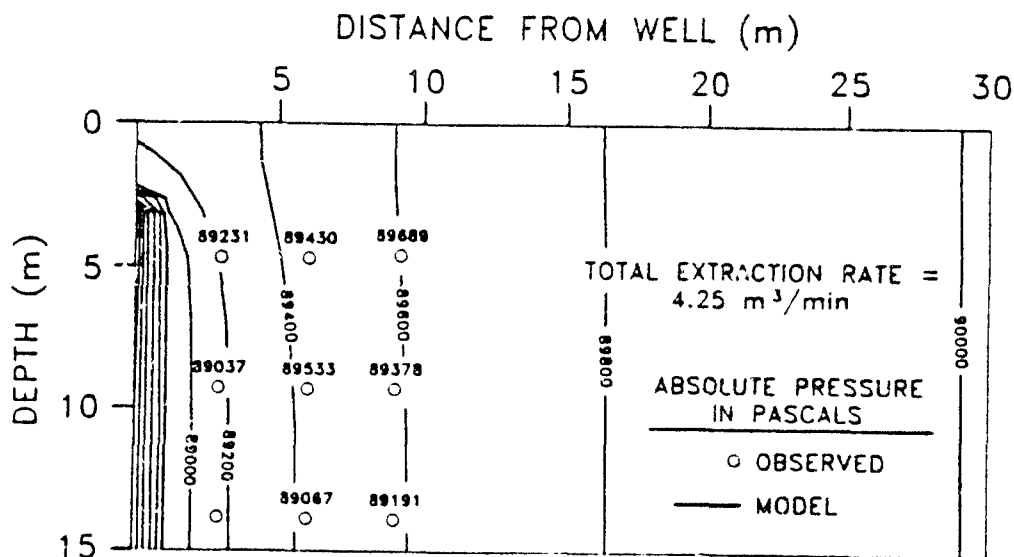


Figure 37. Comparison of Observed and Modeled Air Pressure in the Vicinity of the 4.25 m³/Minute Single-Vent Test With a No-Flow Boundary at Land Surface.



Two methods were used to predict the performance of the Hill AFB system. The first method is an empirical comparison of the single-vent test and the column vent test performed on soil removed from the site. The second method is an idealized theoretical model based on vapor-liquid equilibrium of the components of JP-4. These results provide a range of estimated performance for air flow through an ideal column of contaminated soil. The uncertainties in the amount and distribution of the contamination and venting geometry will change the timetable for removal performance, but may not alter the general behavior pattern.

#### a. Comparison of Single-Vent Test and Column Test

This method was performed by plotting the extraction gas concentrations measured in the single-vent test on the same log-log plot as the column effluent concentrations in the column vent test. The main assumption that must be made using this method is that the soil removed from the site and vented in the column with a linear air flow pattern will act the same as the soil at the site with heterogeneous air flow and contamination. This is certainly not true, but column behavior may provide a first approximation to full-scale system behavior.

Figure 38 shows the plot of concentration versus scaled time for both tests. Hydrocarbon concentrations are shown as a function of the amount of air extracted from an affected soil volume. The points for the column test were plotted by dividing the volume of air extracted by the volume of soil in the column. The early non-linear portion of this curve may be due to dead zones in the tubing during start-up at a flow rate of  $0.028 \text{ m}^3 \text{ air/m}^3 \text{ soil}$  (corresponds to less than 5 minutes in the column test). The later portions of the column test data exhibit a linear log-log relationship. The concentration data for the single-vent test were placed on the same graph by assuming an affected soil volume. This soil volume was chosen by noting the point in the test at which the calculated hydrocarbon concentration began to drop off, on the order of 1330 standard cubic meters of air extracted. It is assumed that at this point the equilibrated soil gas in the affected soil volume had been cleared, causing a drop in concentration as volatilization became the rate-controlling step. Assuming a porosity of 0.3, this results in an affected soil volume of  $157,000 \text{ ft}^3$  ( $4440 \text{ m}^3$ ). With this basis, the single-vent test results were plotted with the column test results. Agreement with the linear fit is quite poor in the early portion of the test as the soil gas was cleared, but as volatilization became important, the points approach the linear column test fit.

The approach of the single-vent test points to the column test line allows an order-of-magnitude projection of system behavior using the line. However, a critical point must be made when choosing the volume of soil to be treated. Factors involved in the uncertainty of this choice are the actual contaminated soil volume and the applicability of the soil sample vented as an average of the soil contamination at the site. Since the soil sample used was from the cuttings from the drilling of the single vent test extraction vent, it is believed to be a good approximation for a composite sample from 0 to 50 feet (0 to 15.2 meters) depth at the average soil contamination, except for the most volatile components that were lost. However, the most volatile components are removed quickly during venting and would thus would not have a great effect on the long-term behavior. Assuming a soil volume of  $1,125,000 \text{ ft}^3$  ( $31,856 \text{ m}^3$ ), the variation of extraction gas concentration with time, based upon the logarithmic linear fit and an extraction flow rate of 3000 scfm ( $1.42 \text{ standard m}^3/\text{second}$ ), is shown in Figure 39.

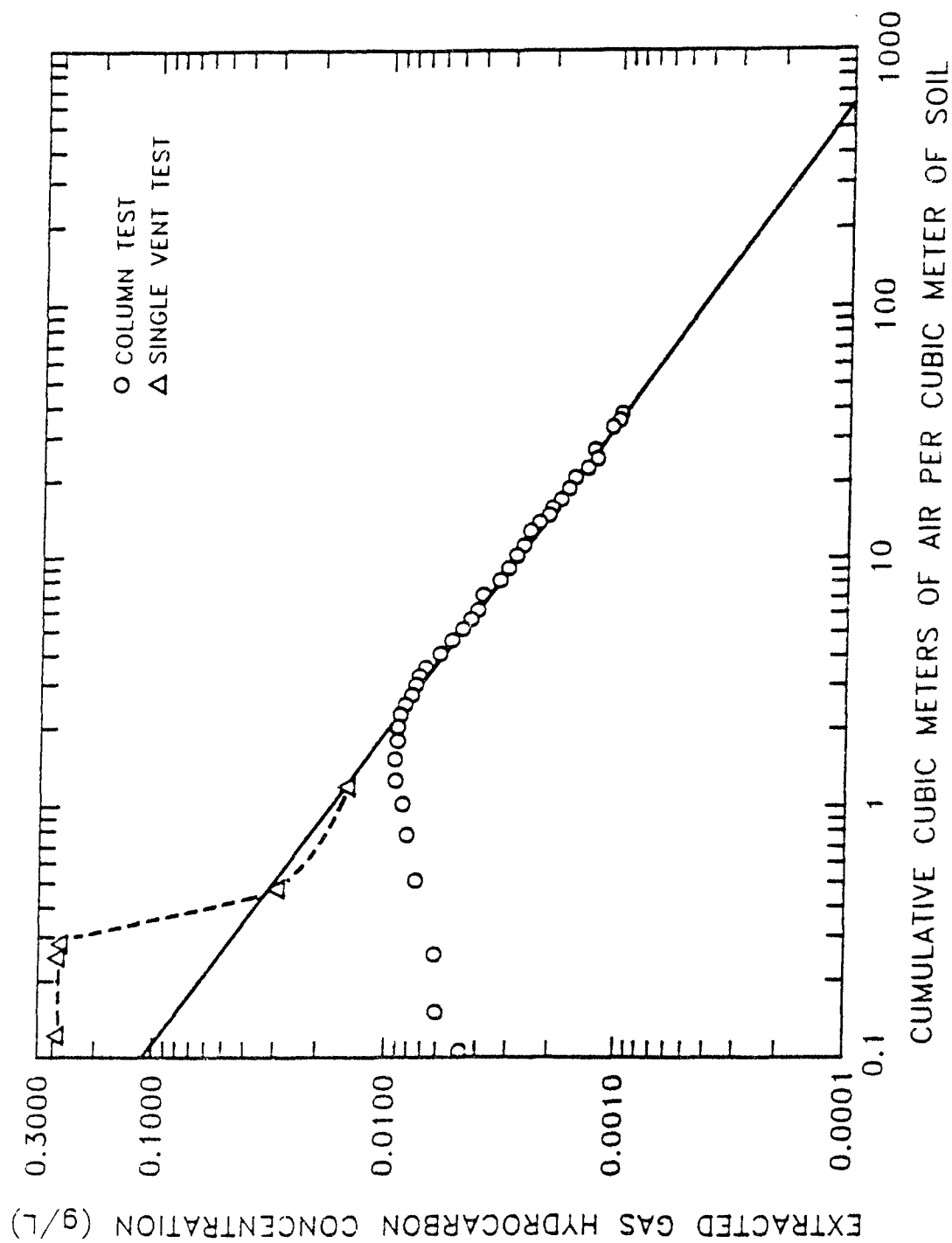


Figure 38. Comparison of Single Vent Test and Column Test Gas Concentration Results.

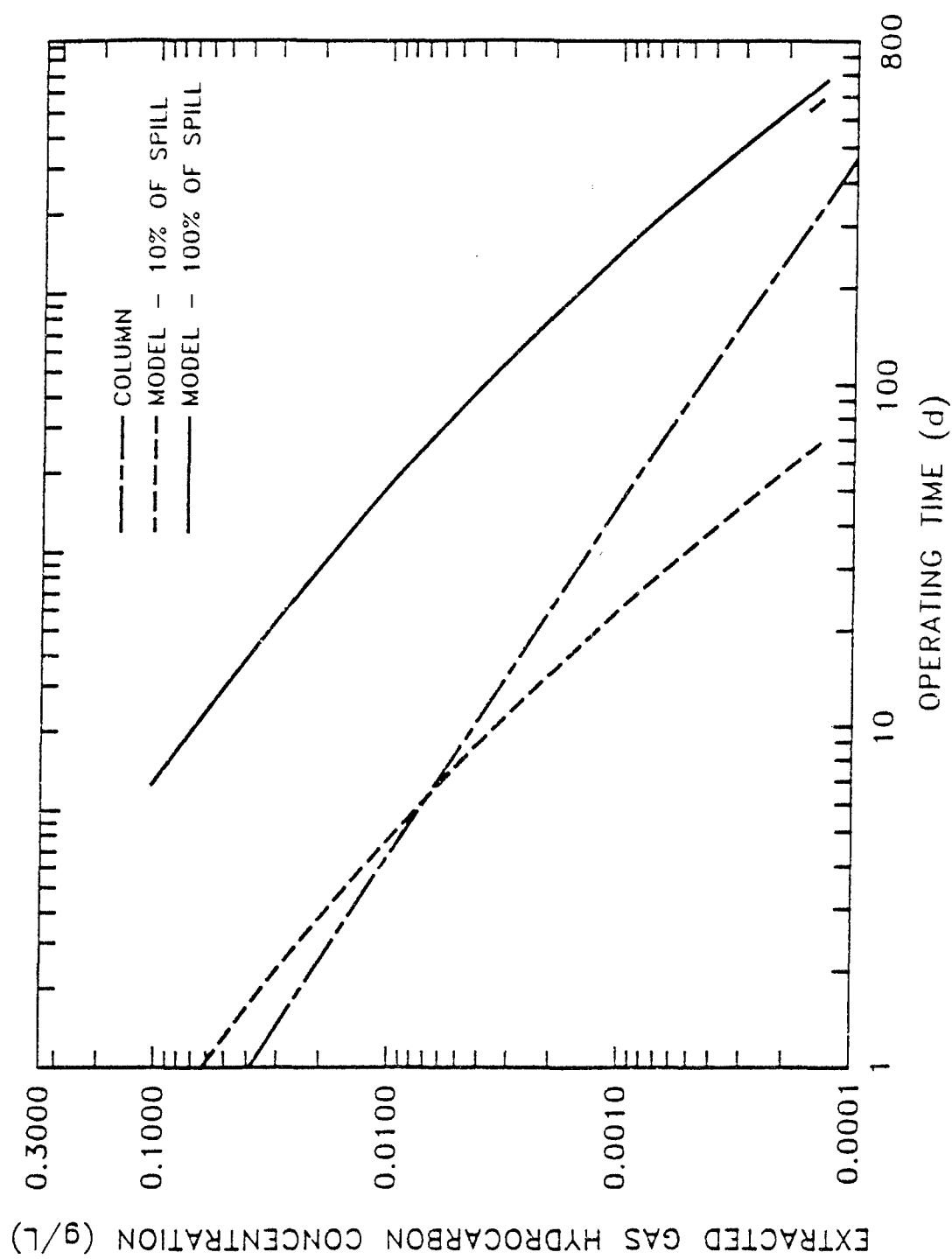


Figure 39. Extraction Gas Concentration Estimates - Extrapolation of Column Test and Raoult's Law Equilibrium Model.

## **b. Ideal Vapor-Liquid Equilibrium**

Estimates of extraction gas concentration may also be made by calculating vapor concentrations in equilibrium with soil contaminants. The model used here is an ideal model, in which the entire air stream comes in even contact with the hydrocarbons, and Raoult's Law is used to approximate the equilibrium concentrations. A computer program, described in Section V.D.5, was written to calculate the vapor concentrations with time, taking into account the depletion in the liquid-phase as species volatilize. Using input of JP-4 weight fractions and assuming a 3000 scfm (1.42 standard m<sup>3</sup>/second) extraction rate, the results shown in Figure 39 were obtained. Hydrocarbon concentration in the extracted gas is dependent on the amount of air contacted per initial weight of fuel. The curve exhibits some deviation from the empirical logarithmic linear relation.

To predict concentration behavior with time, both the initial amount of JP-4 and the extraction flow rate must be assumed. Results were derived for cases of approximately 10 and 100 percent of the initial spill (7,500 and 75,000 kg). This factor of 10 was used to bracket the expected system behavior. The extracted gas concentration behavior resulting from these two cases are also shown in Figure 39. It may be seen that these cases bracket the extrapolated column results. As will be shown in Section V.D.5, the actual results obtained during operation of the full-scale system more closely followed the 100% initial spill mass curve, both in magnitude and shape. Thus, it is seen that projection of removal behavior is an uncertain undertaking. Use of an equilibrium model requires accurate knowledge of contaminant mass present, and small-scale column testing as performed, with one-dimensional gas flow, is unlikely to accurately represent field conditions.

## **2. Application of Flow Modeling to Full-Scale Vent Spacing**

At the point in time during which the pilot studies were conducted and the full-scale demonstration system design was being developed, the state-of-the-art in vent spacing and placement in the literature was based on a "radius of influence" indicated by a radial distance corresponding to a given vacuum level. Although this approach is a definite step forward from a rule-of-thumb approach and will work well for simple systems, it suffers from some major problems which arise since vacuum level is not a direct measure of air flow at any point in the soil. The pressure-based radius ignores the relationship of permeability to the flow-pressure correspondence. For instance, in the case of a layered site (see Reference 13) of sand and clay, in which the screened portion of the extraction vent intersects both layers, there will be much greater flow in the sandy zones than the clay zones (corresponding to faster removal), but the vacuum will be evidenced farther from the vent at steady-state in the clay zones due to the lower permeability. In this case, a design procedure based on a pressure-based radius of influence may yield a much larger vent spacing than would be optimal. Other problems with this approach could be seen in cases of vents with overlapping radii of influence. In the region of overlap, vacuum levels will be increased, but flow rate will decrease. It is possible to have poor treatment but elevated vacuum levels.

Using the results of the single-vent pilot study and air flow modelling, a vent spacing procedure based upon air flux in the soil was produced. Since removal rates are much more dependent on air flow than upon pressure, this procedure may be more closely linked to performance of the system.

Figures 40 and 41 present plots of air flux in the soil at various depths as a function of distance as calculated for the Hill AFB conditions by the FEMAIR model for a 150 scfm extraction rate. Figure 40 presents results for a perfect surface barrier, and Figure 41 presents results in the case of no surface barrier. The plots show a logarithmic relationship of flux with distance, with the results for the surface barrier case representing a straight line, as would be expected for pure radial flow. Flux is a function of depth near the vent in the case of no surface barrier, but flux becomes less of a function of depth farther from the vent. The figures also show that the "reach" of a vent is decreased in the absence of a surface barrier, evidenced by a faster drop in flux with distance in Figure 41 than in Figure 40. With the greater "reach" comes higher vacuum requirements at the same extraction rate.

These flow modeling results were used to estimate a vent spacing to meet a performance standard based on air flux in the soil. In this approach, an average soil concentration is used to provide a total air volume necessary to reach a given removal performance. The vent spacing may then be set by assuming the entire soil volume is at the flux level of the point of the vent spacing of the flux versus distance plot of a single vent operation.

A rough design calculation for the Hill AFB demonstration would assume a soil content of 26,000 gallons ( $7.08 \times 10^7$  grams) in  $7.2 \times 10^5$  ft<sup>3</sup> ( $20,400$  m<sup>3</sup>) or 3500 grams/m<sup>3</sup>. For the purposes of vent design, a performance goal of 50 percent removal by volatilization in six months was desired. From the equilibrium removal model, approximately 50 liters per gram of initial JP-4 mass is estimated to be required for 50 percent removal, amounting to  $3.54 \times 10^6$  liters, or  $1.25 \times 10^8$  ft<sup>3</sup>. For a six month operation, this corresponds to 480 scfm. Assuming that three vents are operating at one time, the curves of Figures 40 and 41 will provide an estimate of flux with distance.

With an average contamination of 3500 grams of JP-4 per cubic meter and 50 liters of air per gram of JP-4 contact necessary, each cubic meter must come in contact with a fresh 175,000 liters of air over the period, or 0.675 standard liters per minute. Assuming radial flow, the affected volume around the vent is  $\pi r_s^2 h$ , where  $r_s$  is the vent spacing and  $h$  is the vent depth. The total flow must pass through an area of  $2\pi r_s h$  at the vent spacing, so the flux at a distance  $r_s$  from the vent is

$$\text{Flux} = \frac{\left(0.675 \frac{L}{\text{min m}^3}\right) (\pi r_s^2 h)}{2\pi r_s h} = \left(0.0263 \frac{\text{kg}}{\text{hr m}^3}\right) r_s \quad [10]$$

In the above equation, the flux will have units of (kg hr<sup>-1</sup> m<sup>-2</sup>) if  $r_s$  is measured in meters.

In order to estimate vent spacing, a trial-and-error procedure is used to find the value of vent spacing which causes agreement of flux as calculated by the above equation with that predicted by flow modeling. Flux values for several vent spacings are given in Table 13.

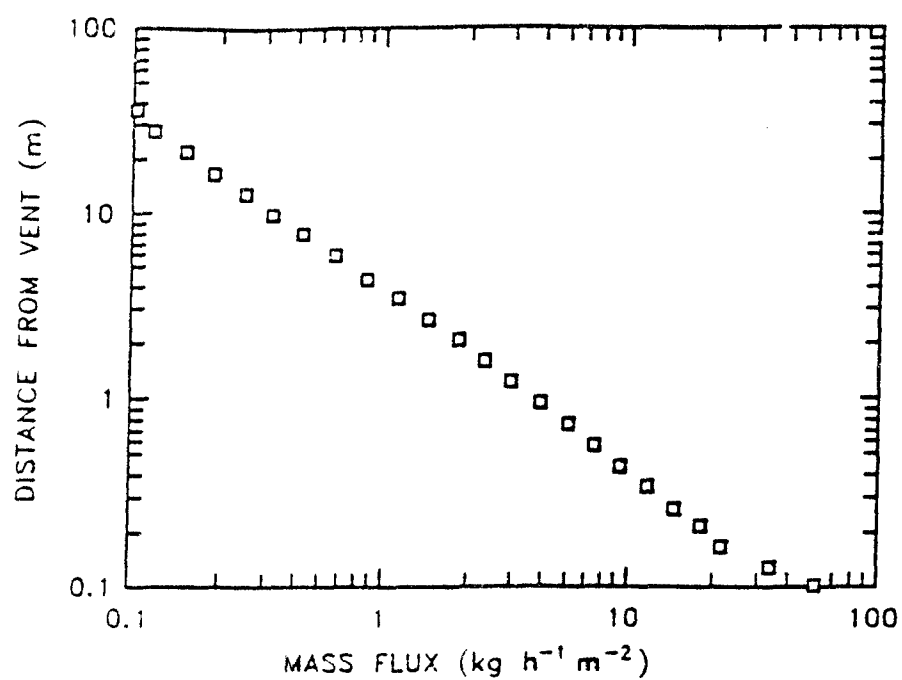


Figure 40. Variation of Flux With Distance for Single Vent Operation With Surface Barrier.

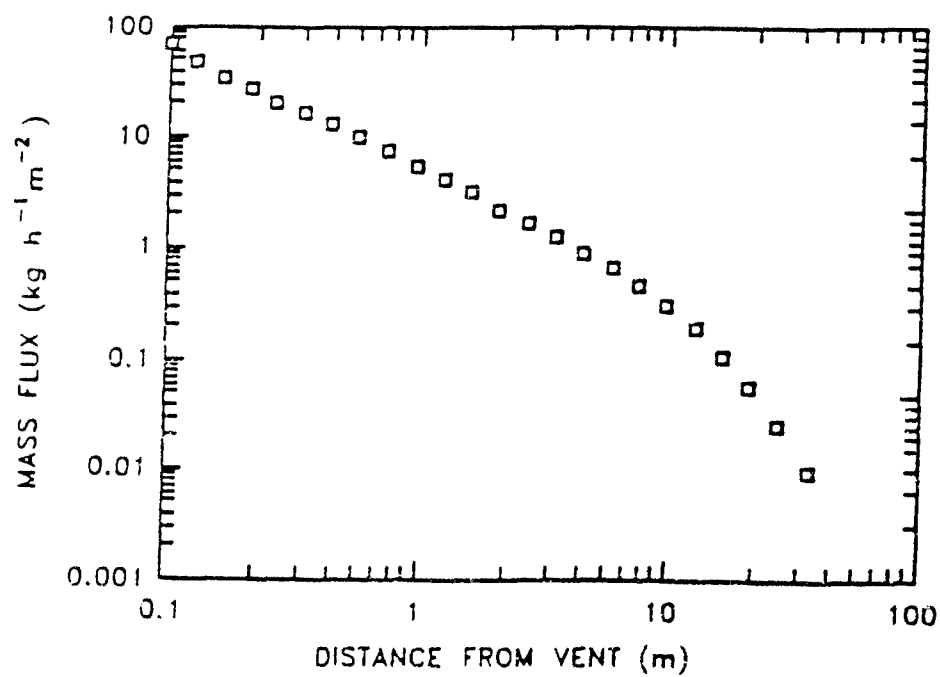


Figure 41. Variation of Flux With Distance for Single Vent Operation With No Surface Barrier.

TABLE 13. CALCULATION OF PERFORMANCE-BASED VENT SPACING

DISTANCE, METERS	CALCULATED FLUX* NEEDED	FLUX* WITH NO BARRIER AT 150 CUBIC FEET PER MINUTE EXTRACTION RATE	FLUX* WITH BARRIER AT 150 CUBIC FEET PER MINUTE EXTRACTION RATE
2	0.052	2.0	2.0
5	0.130	0.80	0.80
10	0.262	0.25	0.40
15	0.395	0.10	0.25
20	0.524	0.06	0.20
40	1.050	0.01	0.12

\*Flux values listed in ( $\text{kg m}^{-2} \text{ hr}^{-1}$ ).

Agreement between the rough removal performance estimating equation and the flow modeling results appears to range from 10 meters for no surface barrier to about 12.5 meters when a surface barrier is included.

A vent spacing of 40 feet (12.2 meters) in a grid was chosen for the full-scale implementation. This spacing was selected based on the above reasoning, but with two other considerations: (1) the flux/distance relationships will be altered in multiple vent operation, with flux levels decreasing in areas between vents; and (2) flow rates greater than 150 scfm per vent were expected, allowing greater vent spacings. The 40-foot spacing therefore was used to give reasonable balance between conflicting factors for a vent spacing criteria based on a performance goal.

## G. CONCLUSIONS OF PILOT TESTING

The pilot tests described in this section provided valuable information for design of the full-scale venting system that was not available from previous site characterization.

A single-vent pilot test at the site, including measurement of pressures at several points in the soil and extracted gas contaminant concentration, was particularly useful for determining soil characteristics and initial hydrocarbon levels in the soil gas. The soil at the site was found to be highly permeable. A vacuum of only 20 inches of water (5000 Pascals) was necessary to extract 214 scfm (0.1 standard  $\text{m}^3/\text{second}$ ) from a 40-foot (12.2-meter) screened interval. The high permeability of the soil resulted in rapid transient response and a large zone of influence. The concentrations of hydrocarbons encountered in operation of the single-vent pilot test were much higher than expected, on the order of 6% by volume. Gas samples taken for GC analysis were subject to uncertainty due

to possible problems with entrained condensate. Estimates of emissions were made from the known composition of JP-4 jet fuel and from relative weights of hydrocarbon fractions in the GC samples. It is likely that the actual amount of hydrocarbons discharged did not exceed 1335 pounds (610 kg).

The concentration data obtained during the single-vent pilot test were not sufficient to adequately predict full-scale system behavior due to the limited operating period. It is recommended that future pilot tests be operated for an extended period, include a shutdown and restart for determining the importance of diffusional resistance.

The single-vent pilot test provided the most useful information since it most closely simulated operation of the full-scale system. However, valuable data for system design was obtained quickly and inexpensively through *in situ* permeability testing. The results of this type of testing were in good agreement with the results of the single-vent test. *In situ* permeability testing would be valuable in place of a single vent test for small-scale sites and emergency operations or for a quick determination of air permeability to be used for specification of blower capabilities in a pilot system.

The results of *in situ* permeability tests and the single-vent pilot test were used in conjunction with flow modeling to provide an estimate of the vent spacing required in the full-scale system. A rough estimation technique assuming equilibrium removal and averaged soil concentrations and ignoring multiple vent effects provided a vent spacing of 30 to 40 feet necessary at this site for an air extraction rate of 150 scfm per vent to achieve a performance goal of 50 percent removal in six months.

The limited column testing performed in this study was judged not to provide data which can be reliably translated for prediction of system performance in terms of time required for cleanup. It may have generated values in better agreement with the full-scale performance had a composite sample been collected without loss of any volatile components. However, the limitation of column testing in having good air/contaminant contact in a linear flow pattern will cause great uncertainty when extrapolating behavior to model that of a field system. Column testing could be extremely useful, however, for a test of the applicability of venting to questionable situations (Reference 14) or for providing a site-specific correlation of soil concentration to equilibrated soil gas concentration.



## SECTION V

### FULL-SCALE VENTING DEMONSTRATION

#### A. INTRODUCTION

In order to investigate the effectiveness of soil venting as a viable remediation technology applicable to JP-4 jet fuel spills, a full-scale demonstration system was designed and operated at the Hill AFB site. Section B presents a physical description of the venting system, and Section C details the operation of the system during the test. Results are grouped in sections according to topic. Results of hydrocarbon removal by volatilization are presented in Section D, while removal by biodegradation is documented in Section E. Results of *in situ* soil moisture measurements taken during the venting demonstration are presented in Section F. The results of vent configuration tests and air flow modeling are briefly discussed in Section G. Section H presents the results of a test of the enhancement of removal by heating, and Section I details the performance of catalytic oxidation units used for emissions control. The effectiveness of treatment during the nine-month demonstration period is evaluated in Section J. Section K presents estimates of the cost of complete site remediation by soil venting.

#### B. DESCRIPTION OF EQUIPMENT

A conceptual drawing of the Hill AFB *in situ* soil venting demonstration system is shown in Figure 42. The system was composed of three subsystems: (1) a vertical vent array in the area west of the tanks, (2) a lateral vent array below the tanks, and (3) a lateral vent system in a pile of soil excavated from around the tanks. The three subsystems allowed investigation of different vent configurations in the same study. This section will describe the vent, pressure-monitoring point, and manifold designs for each subsystem. The blower and emission control system, common to each subsystem, are described at the end of this section.

##### 1. Vertical Vent Subsystem

Most of the operation at Hill AFB centered around the vertical vent subsystem since most of the JP-4 was found in this area. A photograph of the vertical vent subsystem is shown in Figure 43. This system consisted of 15 vents and 31 pressure-monitoring points, including the vent and nine pressure-monitoring points installed for the single-vent pilot test. Half of the venting area was covered by a surface barrier for comparison of flow patterns with and without a barrier.

##### a. Configuration

The vents were located based on the best knowledge of contaminant distribution, allowing flexibility in operation to investigate several different venting strategies. The vents were arranged in a square grid with a 40-foot (12.2-meter) spacing. Coordinates of the vents are listed in Appendix B. The center line of vents had a 20-foot (6.1-meter) spacing and was aligned from the existing vent installed for the single-vent pilot test to the point of the tank vent pipe from which the spill occurred. Vent spacings in the 40-foot (12.2-meter) square grid were based upon the pilot test and modelling

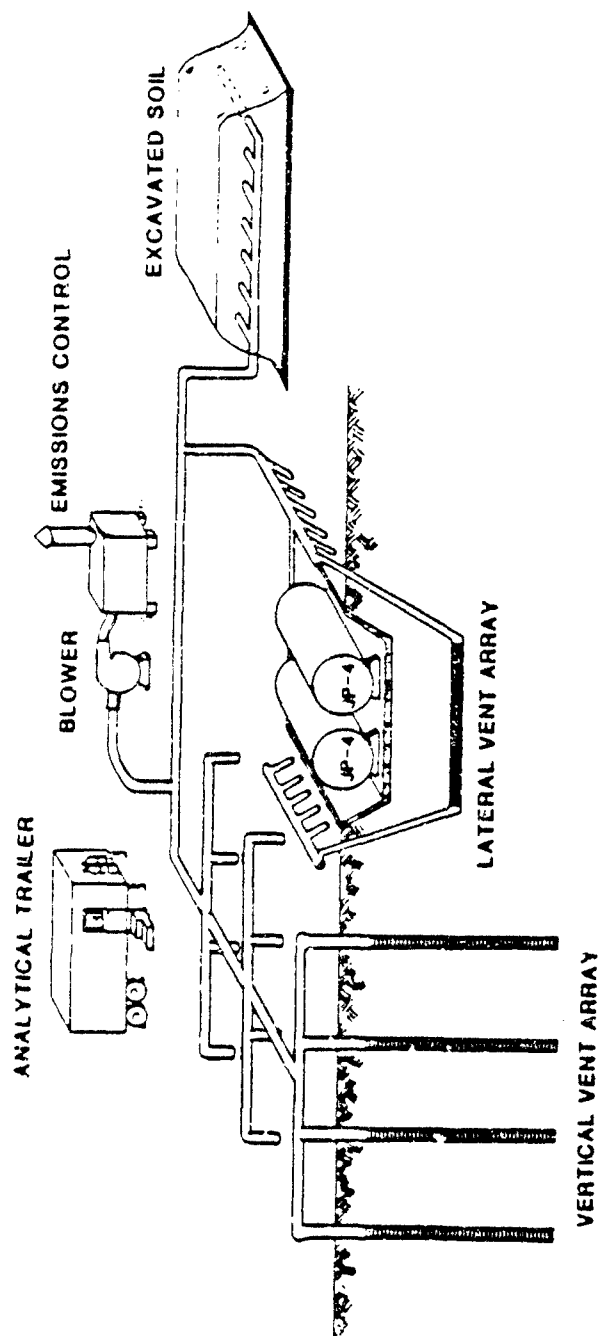


Figure 42. Conceptual Design of *In Situ* Soil Venting Demonstration System at Hill AFB.

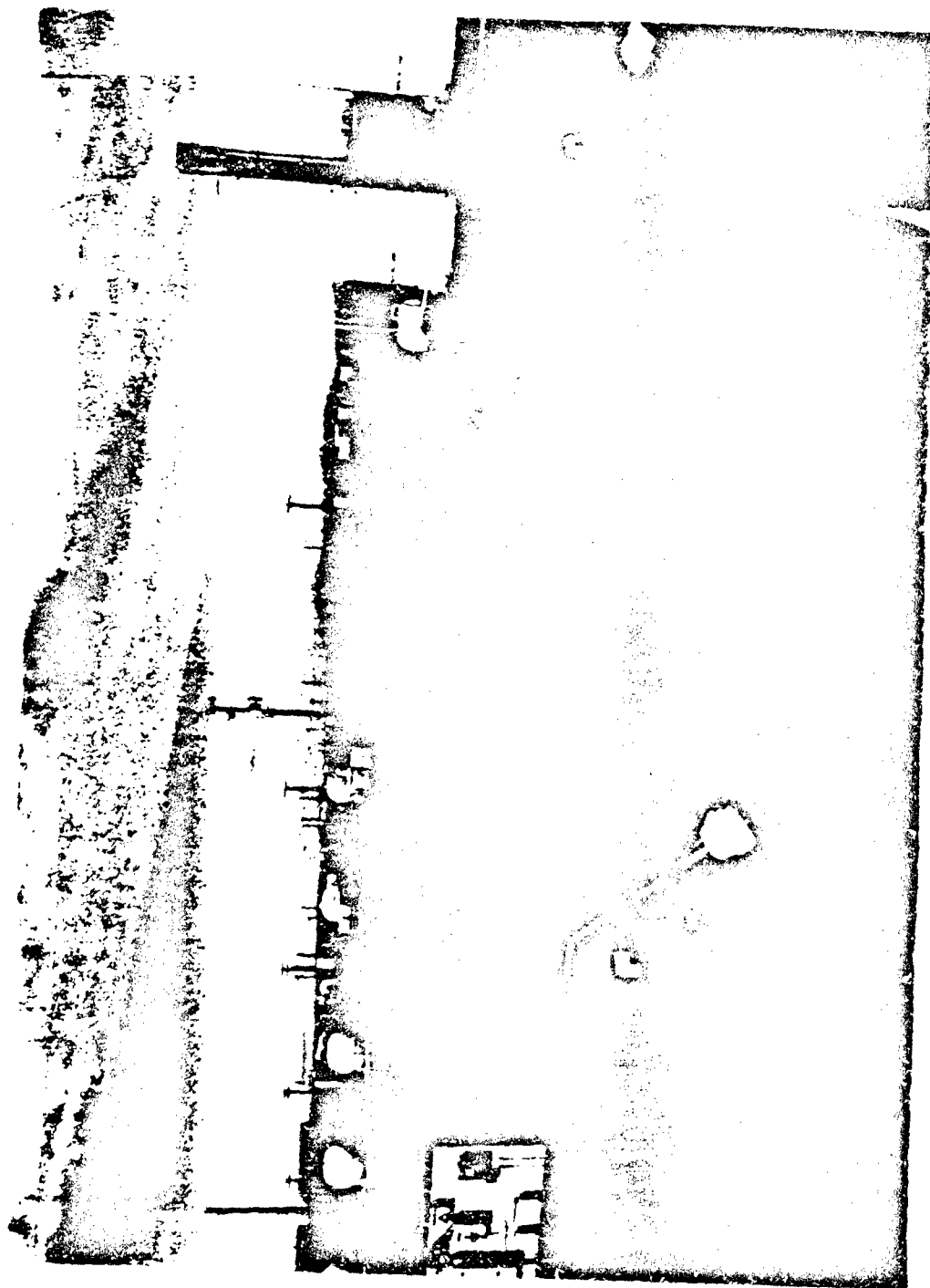


Figure 43. Vertical Vent System Layout.

as described in Section IV.F. The 20-foot (6.1-meter) spacing along the center vent line was not intended to be an optimized vent spacing; rather, it was used to allow operation of several vent configurations. Each vent was valved separately to allow each to act as either an extraction vent or as a passive inlet vent.

Pressure-monitoring points were arranged to allow monitoring of the pressure distribution throughout the system at various depths in order to map air flow patterns resulting from different venting strategies. Coordinates of the pressure monitoring points are listed in Appendix B. A layout of the monitoring points in relation to the vents and other site features is shown in Figure 44. The pressure monitoring points may be broken down into 3 groups: (1) points surrounding a single vent in the area with a surface barrier, (2) points surrounding a single vent in the area without a surface barrier, and (3) points within and extending outward from the vent well system to determine areal vacuum influence. The configuration of the pressure monitoring points was intended to provide pressure distribution data while minimizing the influence of soil inhomogeneities. Each pressure monitoring point was installed in a separate borehole to avoid uncertainty invited by boreholes with multiple completions.

The pressure-monitoring points in the area of the surface barrier were centered around Vent 9 (see Figure 44). This vent was chosen as the center because it could be included in the largest number of vent configuration tests. Eleven pressure monitoring points were placed as close as possible to the diagonal line through Vent 9 and Vent 14 to determine pressure distributions between vents. Six of the pressure-monitoring points were placed at radial distances of 10 and 16.5 feet (3.1 and 5.0 meters) from Vent 9, at depths of 25 and 45 feet (7.6 and 13.7 meters). Pressure monitoring points were not placed at lower depths in this area due to perched water encountered at a depth of 45 to 50 feet (13.7 to 15.2 meters). A pressure-monitoring point was placed on the opposite side of Vent 9 at a distance of 10 feet (3.1 meters) and depth of 25 feet (7.6 meters). Four pressure-monitoring points were placed near the center of the square grid formed by Vents 3, 4, 9 and 10, at depths of 6, 25, and 45 feet (1.8, 7.6, and 13.7 meters). Two additional points were installed at a depth of 30 feet (9.1 meters) at the midpoints between Vent 9 and Vents 3 and 10.

The pressure-monitoring points in the area without a surface barrier were centered around the vent used in the single-vent pilot test, Vent 7. In addition to the pressure monitoring points in place from that test, 8 additional points were installed as close as possible to the diagonal line running through Vents 7 and 12. Between the vents, points were placed at depths of 6 and 45 feet (1.8 and 13.7 meters) at a radial distance of 10 feet (3.0 meters), and at depths of 6 and 25 feet (1.8 and 7.6 meters) at a radial distance of 16.5 feet (5.0 meters). A pressure point was placed on the opposite side of Vent 7 at a radial distance of 10 feet (3.0 meters) and a depth of 25 feet (7.6 meters). Three additional pressure points were placed near the center of the square grid formed by Vents 5, 7, 12, and 13 at depths of 6, 25, and 65 feet (1.8, 7.6, and 19.8 meters).

Four pressure-monitoring points were installed for the purpose of measuring the areal extent of vacuum influence. Points were placed at a depth of 30 feet (9.1 meters), 20 feet (6.1 meters) north of Vent 3, 20 feet (6.1 meters) south of Vent 13 and Vent 14, and as far west as possible of Vent 5.

Points driven to approximately 5 feet (1.5 meters) were also placed throughout the system for further pressure monitoring. The coordinates of these driven pressure points are listed in

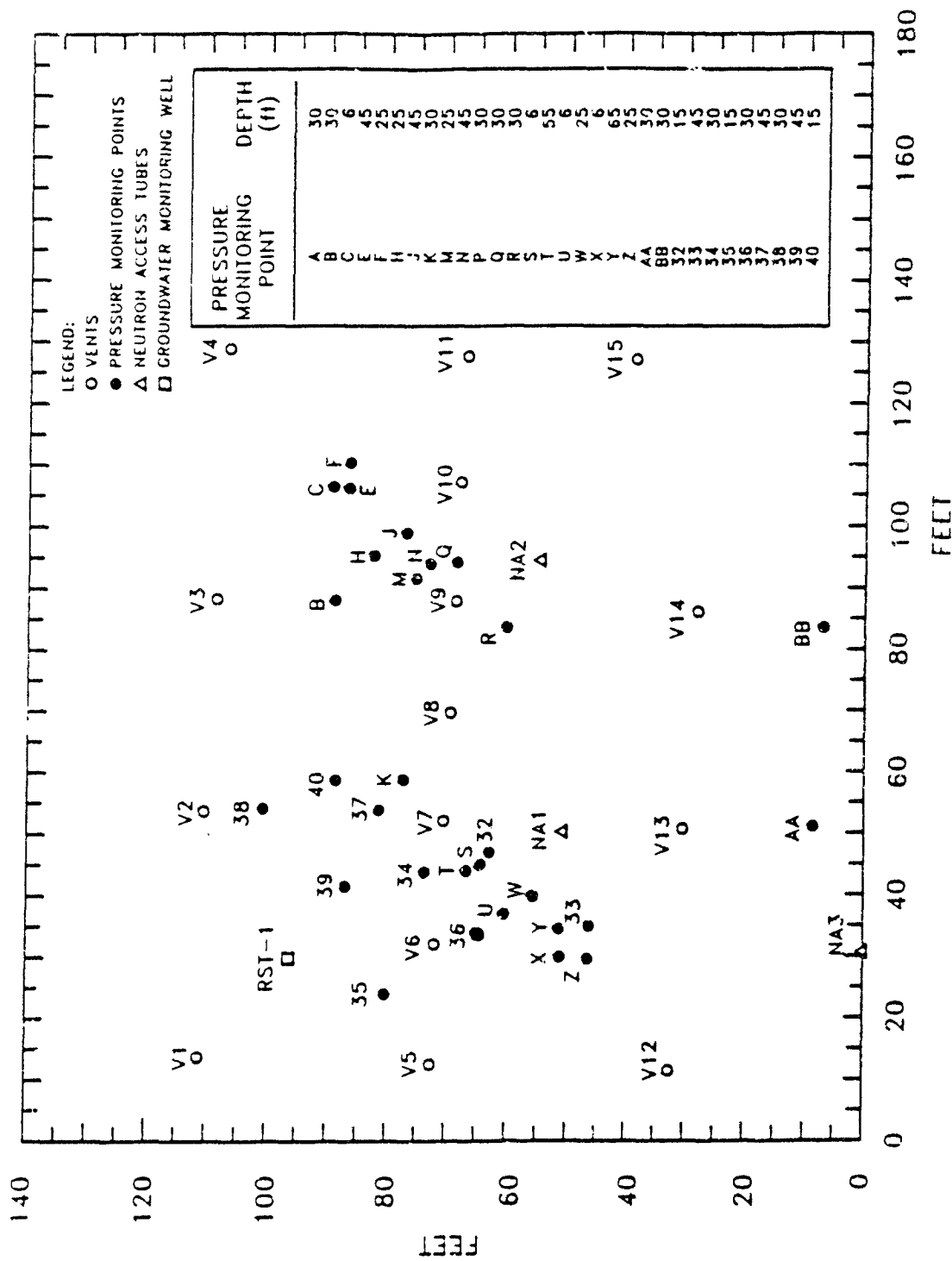


Figure 44. Position of Boreholes in Vertical Vent System.

Appendix B. These points were laid out according to two methods. The first set was placed in basically the same arrangement as the pressure-monitoring points discussed above, but were intended to measure pressures at points in the soil nearer the surface. Driven points were placed near Vents 7 and 9 at various radial distances in order to measure pressure variation near the surface and very close to these vents.

#### **b. Vent Construction**

The vents in the full-scale vertical system were of similar construction to the single vent described in Section IV (see Figure 24). Each 4.5-inch (11.4-cm) OD, 4-inch (10.2-cm) ID vent was installed in a 9.675-inch augered hole. Each vent consisted of a 40-foot (12.2-meter) length of flush-joint Schedule 40 PVC screen (slot width 0.02 inches) installed at a depth of between 10 feet and 50 feet (3.0 meters and 15.2 meters) below ground surface and capped at the lower end. Flush-joint Schedule 40 PVC was used for the riser pipe. PVC cement was used to join all PVC fittings. Stainless steel centralizers were installed to maintain the riser pipe in the center of the borehole. Vents 6 and 10 were constructed in a similar manner with stainless steel screen and riser pipe to allow the injection of hot air.

Each auger hole was backfilled with dry coarse sand to one foot above the screen, using a tremie tube. A 12-inch (30-cm) layer of bentonite pellets was placed on top of the sand, and the hole was grouted to the surface by tremie tube with cement-bentonite (9:1) grout. A concrete collar approximately 2 feet (0.6 meters) in diameter was installed to provide mechanical stability for the vent and to divert rainfall from penetrating the backfilled hole. Each vent extended at least 1 foot (30 cm) above the concrete collar, and was capped with a PVC cap to prevent water infiltration before system installation, and protected with 8-inch (20-cm) diameter steel pipe extending to 3 inches (7.6 cm) below the top of the vent pipe.

#### **c. Pressure-Monitoring Point Construction**

The pressure-monitoring points were installed to measure the pressure at points in the soil throughout the system. Their design also allowed experimental *in situ* permeability studies and extraction of soil gas samples.

The pressure-monitoring points consisted of 1-inch (2.54-cm) OD flush-joint PVC with a 2-foot (61-cm) screened section, capped at the lower end, connected to the remaining upper section of 1-inch (2.54-cm) flush-joint PVC well casing (see Figure 45). The monitoring points were installed in a 4-inch (10.2-cm) augered boreholes. PVC cement was used to join all subsurface PVC fittings. Stainless-steel centralizers were used to maintain the riser pipe in the center of the borehole. Coarse sand was packed to a depth of 1 foot (30.5 cm) above the screens, using a tremie tube. The holes were backfilled with a 12-inch (30.5-cm) layer of bentonite pellets, followed with cement-bentonite grout to the surface to seal against air flow from the surface. The points extended at least 1 foot (30.5 cm) above ground surface, and were capped with PVC caps to prevent water infiltration and protected with 8-inch (20.3-cm) diameter steel pipe extending 3 inches (7.6 cm) below the top of the riser pipe. The PVC caps were drilled and tapped with 1/4-inch (6.4-mm) tubing fittings installed for connection of pressure gauges and sampling lines.

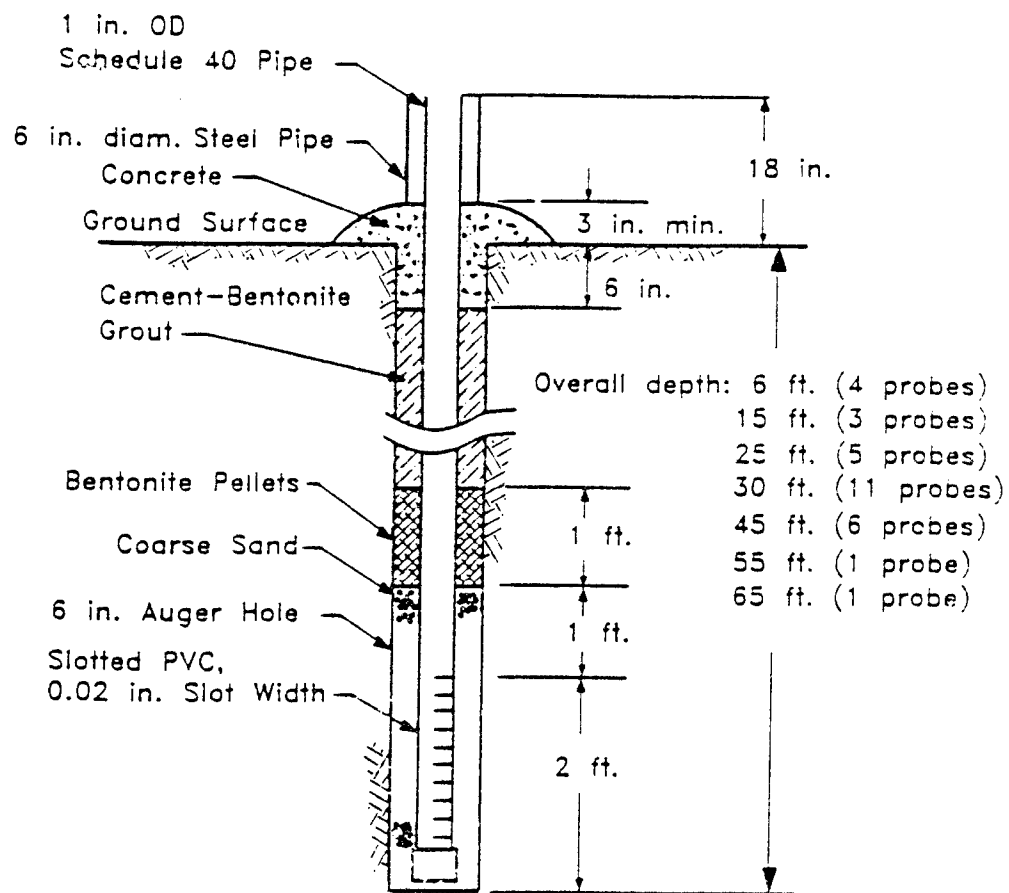


Figure 45. Schematic Drawing of Pressure Probe Design and Installation (3.0 meters) long.

The pressure monitoring points that were driven into the soil at several points in the system were constructed from 1/4-inch (6.4-mm) stainless steel capillary tubing 5 to 10 feet (1.5 to 3.0 meters) long. Radial cuts in the tubing allowed monitoring of pressure at the pointed end of the probe. Pressure gauges were then attached to tubing connections at the other end.

#### **d. Surface Barrier**

A surface barrier was placed over half the venting area to investigate the effects of short-circuit air flow. The barrier covered a rectangular area approximately 80 x 140 feet (24.4 x 42.7 meters), extending from the cement storage tank enclosure on the east to the waste oil berm on the northwest, and 70 feet (21.3 meters) from the center vent line to the north and south.

The surface barrier was installed by scraping the area to a depth of 12 inches (30.5 cm) with a bulldozer, and manually spreading out a 10-mil (0.254-mm) polyethylene sheet followed by one 6-mil (0.152-mm) polyethylene sheet over the area and covering both plastic sheets with the soil that was removed. Edges of the plastic sheeting were overlapped at least 3 feet (0.9 meters) to ensure an effective barrier to air flow. Care was taken to not move or puncture the plastic when covering with soil. The soil was then compacted so that moving the drill rig in the area would not move or puncture the plastic.

The barrier was installed before the drilling of the pressure monitoring points and vents. The soil overlying the plastic sheet was carefully scraped away manually and the sheet was cut to ensure passage of the auger prior to boring.

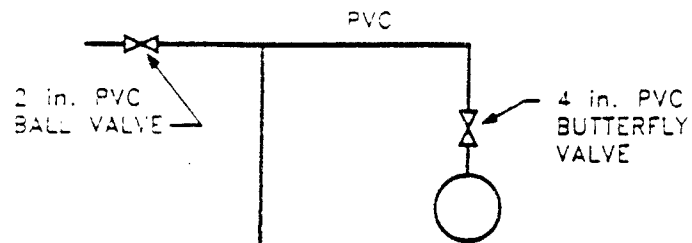
Despite all precautionary digging permits, a water main was struck when drilling for sampling and vent installation. During the escape of water and the repair of the water line, the surface barrier was damaged in a 6-foot (1.8-meter) diameter area around the site of the puncture. After the water main was repaired, the surface barrier was replaced by installing overlapping polyethylene sheets over the damaged area. The barrier patch was then manually covered with soil, and compacted as in the original installation procedure.

#### **e. Vent Head Connections**

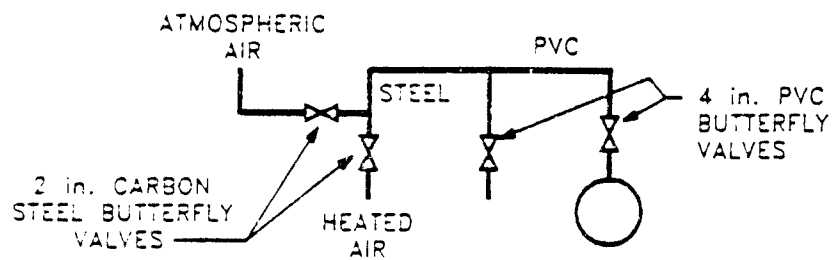
PVC and steel fittings were used to connect each vent to the manifolds. The vent heads were of three configurations (see Figure 46): one for vents at the end of a manifold to allow dilution air (either atmospheric or heated) into the manifold, one for the vents used for heat injection, and another for the remaining vents that did not allow for dilution air. Each of the vents could be operated as a passive inlet vent. The reason for the different configurations is to allow dilution only at the ends of each line, causing a sweeping of the line to prevent large pockets of explosive gas mixtures.

For each of the two configurations not involving heat injection, a 4-inch (10.2-cm) PVC tee was placed atop each vent head. Piping and valving was installed to allow for multiple uses of each vent head. On vents at the end of a manifold, (Vents 1, 4, 5, 11, 12, and 15) piping was installed to allow for use as an inlet air vent, extraction vent, heated air inlet, or dilution air inlet vent. This was accomplished by installing a 4-inch (10.2-cm) PVC butterfly valve above the vent head

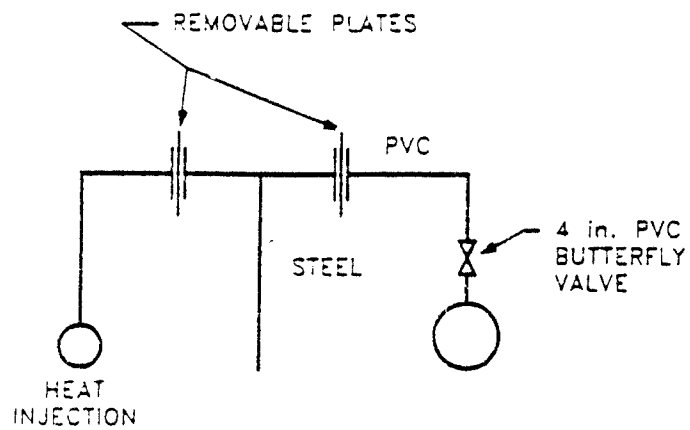




VENTS 2, 3, 7, 8, 9, 13, 14



VENTS 1, 4, 5, 11, 12, 15



VENTS 6, 10

Figure 46. Vent Head Construction.

and at the manifold connection, along with 2-inch (5.1-cm) carbon steel butterfly valves to allow heated air or atmospheric air to be introduced. On all vents that were not end vents or heat injection vents (Vents 2, 3, 7, 8, 9, 13, and 14), piping was modified to allow use as either an inlet air vent or extraction vent. A 4-inch (10.2-cm) PVC butterfly valve was installed at the manifold pipe and a 2-inch (5.1-cm) PVC ball valve was installed to control dilution with atmospheric air.

A 4-inch (10.2-cm) steel flanged tee was placed atop steel Vents 6 and 10. One of the flanges was connected directly to the heated air inlet line. This flange was blanked with a plate when heated air inlet was not desired. The other flanged end was connected to a 4-inch (10.2-cm) PVC line leading to the 6-inch (15.2-cm) PVC manifold line. A 4-inch (10.2-cm) butterfly valve was used to control extraction from the vent. The PVC line could be detached in case the vents were to be operated as inlet vents or with heated air injection (with a blank plate attached to the steel tee flange).

Taps normally containing 1/4-inch (6.4-mm) stainless steel tubing fittings on the vent head connections allowed measurement of vacuum, temperature, humidity, and flow rate, and provided a point for extraction of gas samples.

#### **f. Manifold**

Large-diameter schedule 40 PVC pipe (6 inches) was used to direct flow from the vents to the blower. Pipes were run on supports along the ground, meeting the main north-south 8-inch (20.3-cm) PVC manifold at the center of the vertical system. These ducts were sized to produce less than 10 inches of water (2500 Pascals) pressure drop at a 3000 scfm (1.42 standard meter<sup>3</sup>/second) flow rate. The pipe thickness was adequate to withstand 1000 inches of water (250,000 Pascals) negative pressure differential. The pipes throughout the system were insulated with 2-inch (5.1-cm) fiberglass insulation and wrapped with an aluminum covering to protect them from water. See

#### **g. Neutron Probe Access Tubes**

Soil moisture is a dominant environmental variable in determining soil permeability, and thus air flow and venting effectiveness. To assess changes in soil moisture during venting, three neutron probe access tubes were installed: one each near the center of the covered and uncovered vent areas, and a control tube outside the vent array. Coordinates of these tubes are listed in Appendix B.

Boreholes for the neutron access tubes were drilled to a depth of 50 feet (15.2 meters) with 2-inch (5.1-cm) auger bits. The neutron access tubes consisted of 20-foot (6.1-meter) lengths of 2-inch (5.1-cm) ID thin-walled aluminum tubing, joined with thin-walled brass sleeves and quick-setting epoxy cement, with a drive point fitted at the lower end (Figure 47). The tubes were installed by pushing with the auger rig into the borehole. Each tube section was joined immediately prior to installation. Following tube installation, a concrete collar approximately 2 feet (61 cm) in diameter was installed to provide mechanical stability for each tube and to divert rainfall from penetrating down the backfilled hole. The tubes extended at least 18 inches (45.7 cm) above the concrete collar, and were capped with a friction-fit PVC cap to prevent water infiltration. A 6-inch (15.2-cm) diameter protective steel casing equipped with a drain hole at the base was installed around each tube. The casing extended no more than 2 inches (5.1 cm) above the top of the neutron access tube.

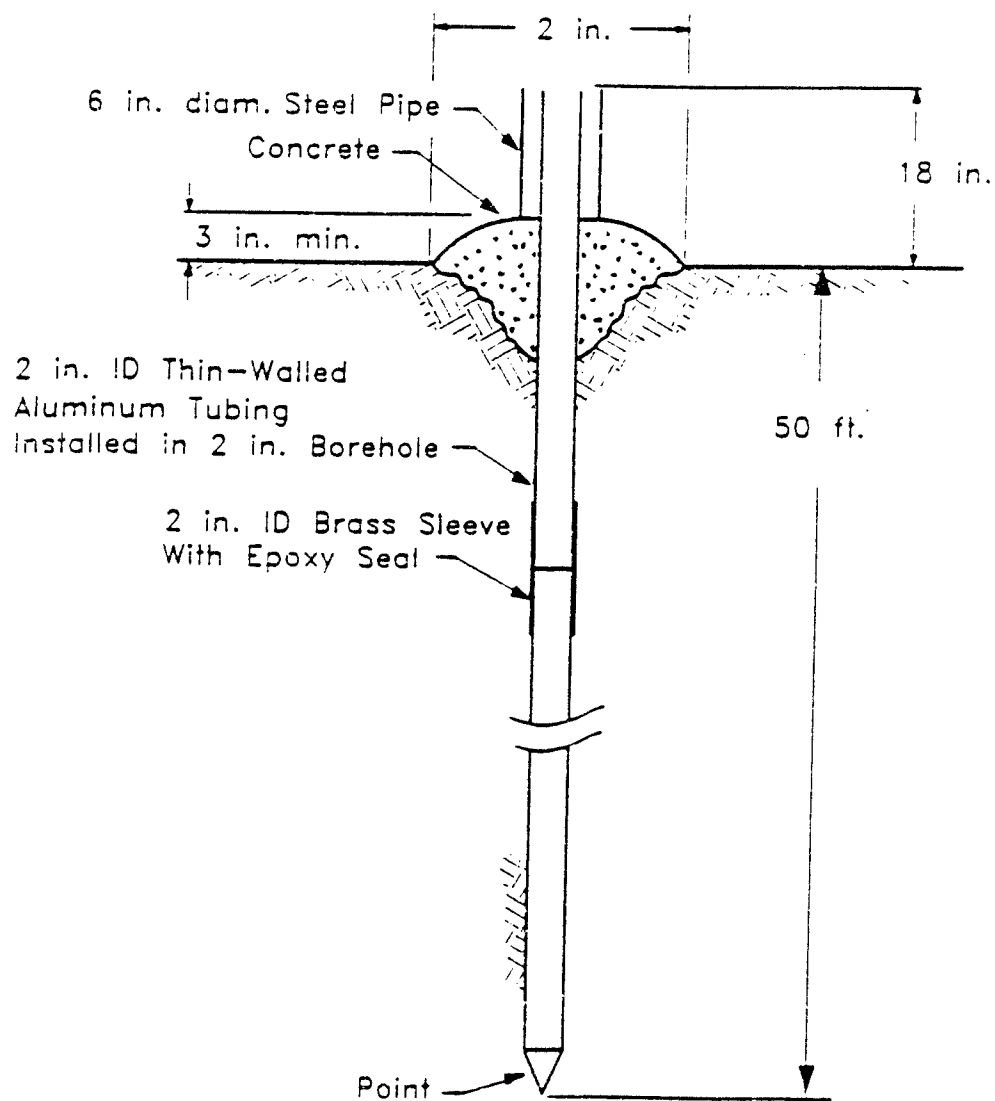


Figure 47. Schematic Drawing of Neutron Access Tube Design and Installation.

## **2. Lateral Vent Subsystem**

The lateral vent subsystem was installed in October 1987 at the time of the tank excavation as shown in Figure 48. The lateral vents were installed to decontaminate the soil beneath the tanks that was not removed during the tank excavation. This area was covered by fill material and a concrete pad. The tanks were enclosed within a concrete dike.

### **a. Configuration**

The six lateral vents lie at a depth of approximately 20 feet BLS and approximately 15 feet apart, running east to west across the tank area (Figure 49). Blank flanges were used as needed to allow each lateral vent to act as either an extraction vent or as a passive air inlet vent.

### **b. Vent Construction**

Six 35-foot (10.7-meter) long trenches were dug across the excavated area 5 feet (1.5 meters) from the floor of the excavation to approximately 19 feet (5.8 meters) BLS. The trenches angle from 12 inches (30.5 cm) wide at the bottom to 3 to 5 feet (0.9 to 1.5 meters) wide at the top. A 6-inch (15.2-cm) layer of washed gravel was poured into the trench, above which was placed the vent pipe. The vent pipe consisted of 4-inch (10.2-cm) perforated polyethylene pipe wrapped in filter fabric, which was run the length of the trench. Washed gravel was poured on top of the vent pipe to a depth of 1 foot (30.5 cm). The remainder of the trench was filled with concrete to prevent short-circuit flow of air. Non-perforated polyethylene pipe was run from the concrete surface up the sides of the excavation to the surface. The excavation was lined with plastic before fill material was laid for construction of the tank enclosure.

### **c. Pressure Monitoring Point Construction**

Probes were placed in the soil during lateral system installation and sampling for the purpose of pressure monitoring and extraction of soil gas samples. The position of these probes is shown in Figure 21, and coordinates are listed in Appendix B. Fourteen probes were placed at a 5-foot (1.5-meter) depth from the excavation floor (19 feet BLS) in the sampling holes set on a 17.5-foot x 17.5-foot (5.3-meter x 5.3-meter) rectangular grid. To this was added an array of probes which was used to provide information on flow patterns between the lateral vents. These 18 probes were placed at depths of 2.5, 5, and 7.5 feet (0.8, 1.5, and 2.3 meters) from the excavation floor, and at distances of 3.75, 7.5 and 11.25 feet (1.1, 2.3, and 3.4 meters) from the vent pipes, in the spaces between the southernmost three vents.

The soil gas probes were constructed as shown in Figure 50. A 6-inch (15.2-cm) length of schedule 80 PVC pipe was perforated with at least twelve 0.328-inch (0.833-cm) diameter holes. Stainless steel screen was rolled up and fit inside the tube to hold out sand. Solvent-welded caps were placed on both ends of the tube. One cap was drilled and tapped for installation of a 1/4-inch (6.2-mm) pipe-to-tubing adaptor, sealed with Teflon® tape. Thick-walled 1/4-inch (6.2-mm) polyethylene tubing was run from the probe to the surface. The probes were placed at the bottom of the boreholes, and surrounded and covered with pea gravel to a height of 14 inches (35.6 cm). The gravel was covered with at least 10 inches (25.4 cm) of sand mix concrete, with the remainder

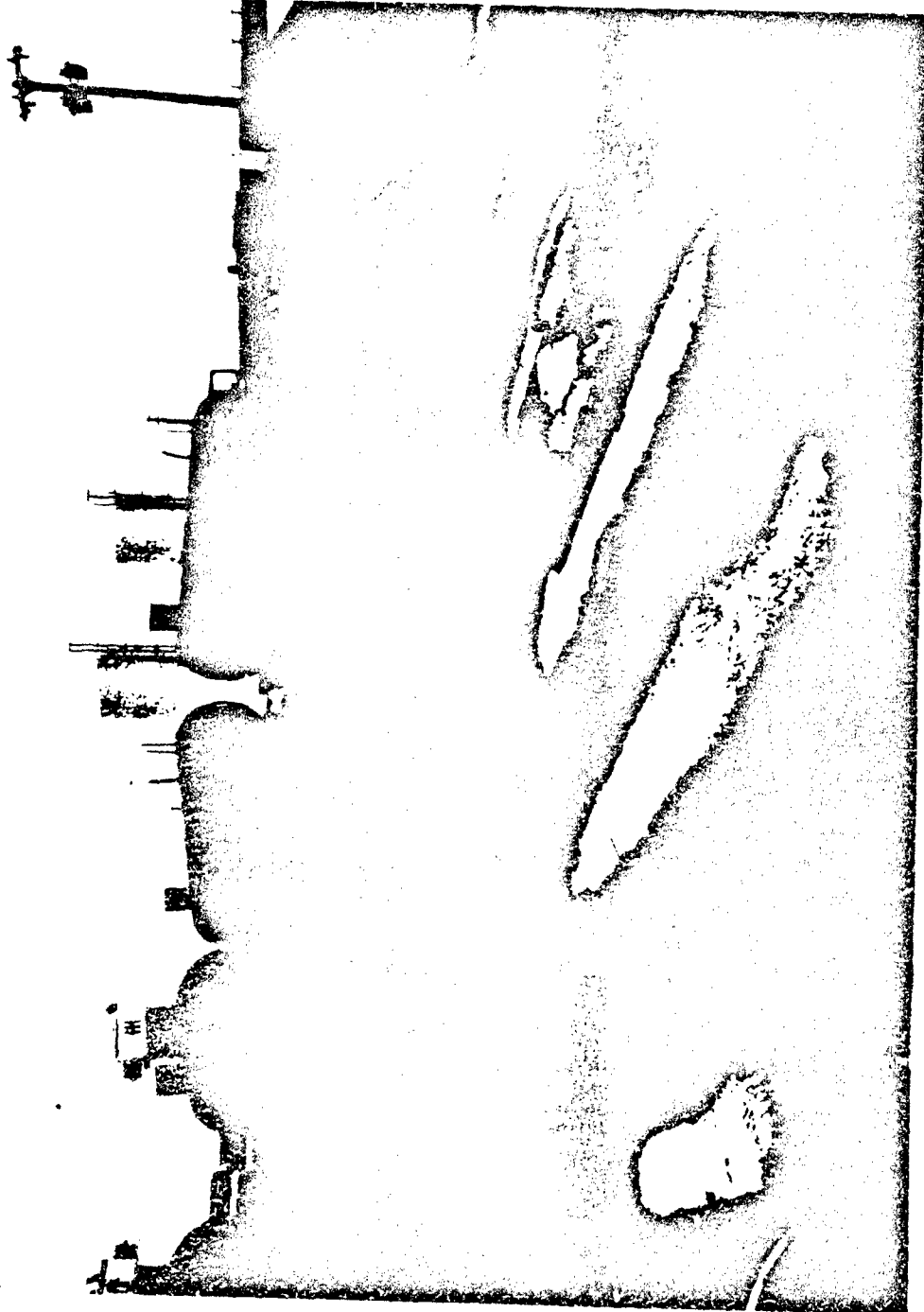


Figure 48. View of Lateral Vent System During Installation.

# Lateral Vent System Side View

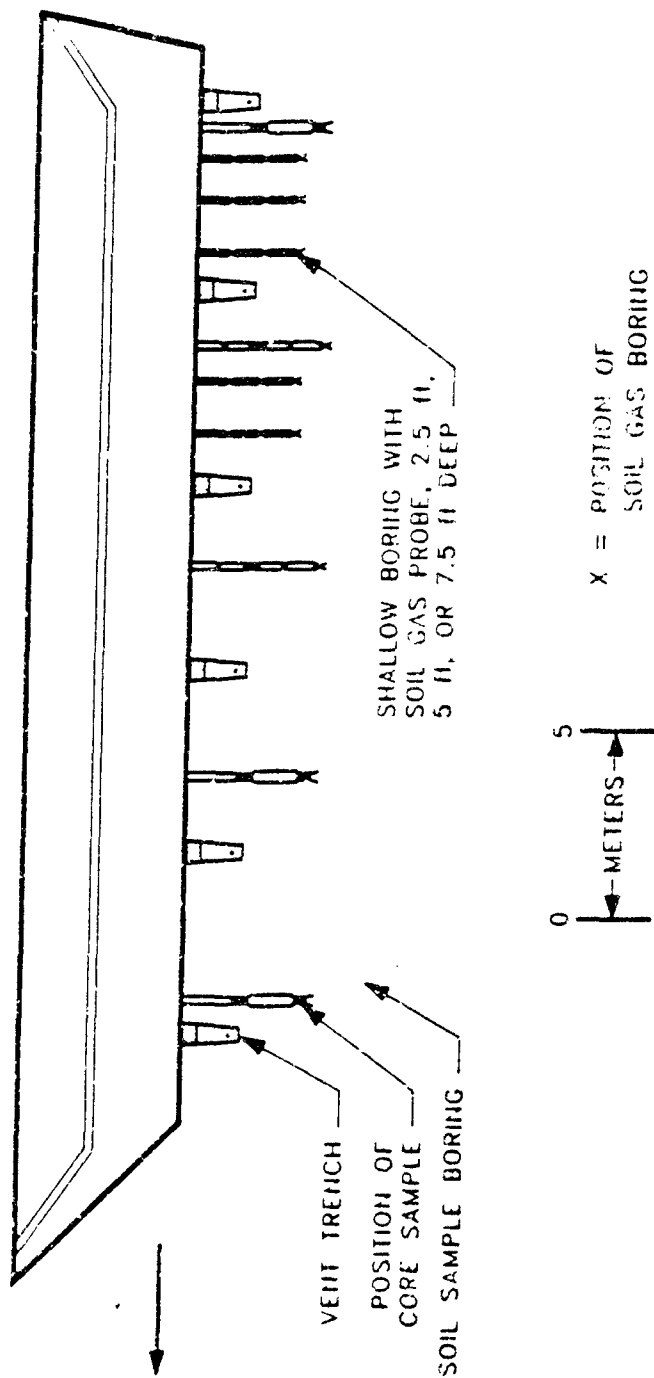


Figure 49. Lateral Vent System Side View.

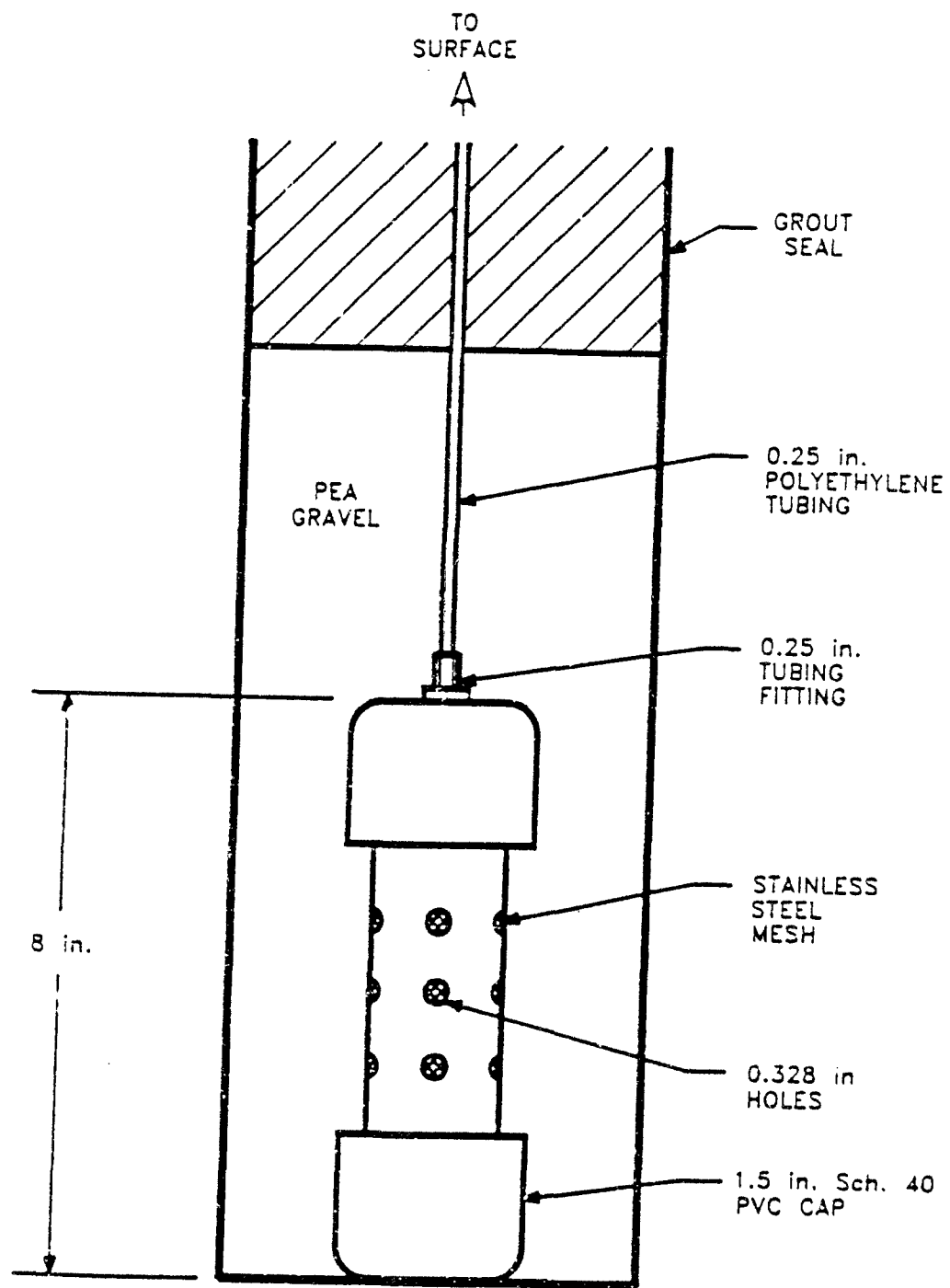


Figure 50. Lateral System Soil Gas Monitoring Probe.

of each hole backfilled. The polyethylene tubes were manually placed in 4-inch (10.2-cm) deep trenches across the floor of the excavation and up the sides to the surface. The trenches were manually backfilled to protect the tubes from damage during later installation of the concrete trench liner.

#### **d. Manifold**

The lateral system vent pipes were connected to a separate north-south 6-inch (15.2-cm) PVC manifold parallel to the east side of the tank enclosure. The end of the vent pipes exposed on the west side of the tanks were capped. An orifice plate and a valve were installed in the lateral system manifold for flow measurement and control. See Section V.B. for more piping details.

### **3. Excavated Soil Pile Subsystem**

The excavated soil pile venting subsystem consisted of a series of lateral vents placed in the contaminated soil removed during the tank excavation. Approximately 52,000 ft<sup>3</sup> (1470 m<sup>3</sup>) of soil originally contaminated to greater than 1 percent by weight of hydrocarbons were removed and formed into a non-compacted pile with a volume of approximately 58,000 ft<sup>3</sup> (1640 m<sup>3</sup>).

#### **a. Pile Preparation**

The excavated soil was formed into a pile 160 feet (48.8 meters) long with a nearly triangular cross section 43 feet (13.1 meters) at the base and 17 feet (5.2 meters) high. Because of erosion of the pile due to wind and rain, the pile was dressed and covered. Approximately 5 feet (1.5 meters) from the ridge of the pile was removed, to reduce the pile height to 12 feet (3.7 meters) above ground surface. The removed soil was allowed to slide down the sides of the pile. The sides of the pile were then dressed and compacted to a slope of no greater than 35 degrees (1:1.43). The pile was then completely covered with geotextile matting. The matting consisted of woven wood fabric with netting on both sides, with mesh size no larger than 1 inch x 2 inch, and at least 48 inches in roll width. The matting was applied vertically in accordance with the manufacturer's specifications. The edges were stapled consistent with the manufacturer's specifications, and engaged the edges of both adjacent strips for adequate anchorage.

#### **b. Vent Construction**

The vents were constructed from 4-inch (10.2-cm) perforated polyethylene drainage pipe with filter fabric cover. The eight vents were placed horizontally in the pile as it was formed at a nominal level of 5 feet (1.5 meters) high and 18 feet (5.5 meters) apart. The submerged length of the vents was about 36 feet (11.0 meters).

#### **c. Pressure Monitoring Point Construction**

Pressure monitoring points were pounded into several locations in the pile to monitor air flow within the pile. The pressure monitoring points were constructed from 1/4-inch (6.4-mm) stainless steel capillary tubing 5 to 7 feet (1.5 to 3.0 meters) long. Radial cuts in the tubing allow monitoring of pressure at the pointed end of the probe. Pressure gauges were attached to tubing connections at the other end.



#### **d. Manifold**

The ends of the vent pipes on the northern side of the pile were connected to an insulated 6-inch (15.2-cm) PVC manifold leading to the main manifold upstream of the blower and dilution system. The other ends of the vents were sealed with rubber disk inserts followed by concrete.

### **4. Blower/Emission Control System**

The blower/emission control system was common to the three venting subsystems, providing vacuum for inducing air flow, and treating emissions as necessary to meet regulatory requirements. Two separate catalytic destruction units were employed, one with a fixed catalyst bed and the other with a fluidized bed.

The blower/emissions control system provided a vacuum source for extraction of up to 1500 scfm (0.71 standard m<sup>3</sup>/second) from the soil contaminated with JP-4 jet fuel and destruction of up to approximately 99 percent of the hydrocarbons in the extracted gas. A schematic of the system is shown in Figure 51 and a photograph is included as Figure 52. The system consisted of manifold piping, flowmeters, a knock-out drum, flame arrestors, three vacuum blowers, two rental catalytic oxidizers, exhaust stacks, and the heated gas injection line. The blower/emissions control system was placed outside the vertical vent area to comply with fire codes for the fuel storage area.

#### **a. Manifold Piping**

A schematic of the piping connections from the three subsystems to the blower/emissions control system is shown in Figure 53. Six-inch (15.2-cm) insulated PVC pipe was used for each manifold pipe to the point where it joined an 8-inch (20.3-cm) main pipe that carried vapors to the blower/emissions control system.

#### **b. Flowmeters**

Orifice plate flowmeters were installed on the lines leading from each subsystem. Orifice plates were also installed on the lines from each blower to each catalytic oxidation unit.

The orifice plates were designed with radius taps. The orifices were sized to provide a 10-inch water column (2500 Pascals) pressure drop at the maximum point of its range. Therefore, plates of several different sized orifices were necessary to cover the entire flow range encountered. For the 8-inch (20.3-cm) manifold line, orifices with diameters of 2.25, 3, 4, and 6 inches (5.7, 7.6, 10.2, and 15.2 cm) were used. For the 6-inch (15.2-cm) manifold line, 3.25-inch and 4.5-inch (8.3-cm and 11.4-cm) orifices were used. A 2-inch (5.1-cm) diameter orifice was used in the 4-inch (10.2-cm) line.

#### **c. Knock-Out Drum**

The knock-out drum was used to protect the rotary-lobe blowers from particulates or liquid droplets suspended in the gas stream. Design of the demister was intended to protect the rotary lobe blowers from a variety of dust and droplet sizes, as would be expected in an extracted soil

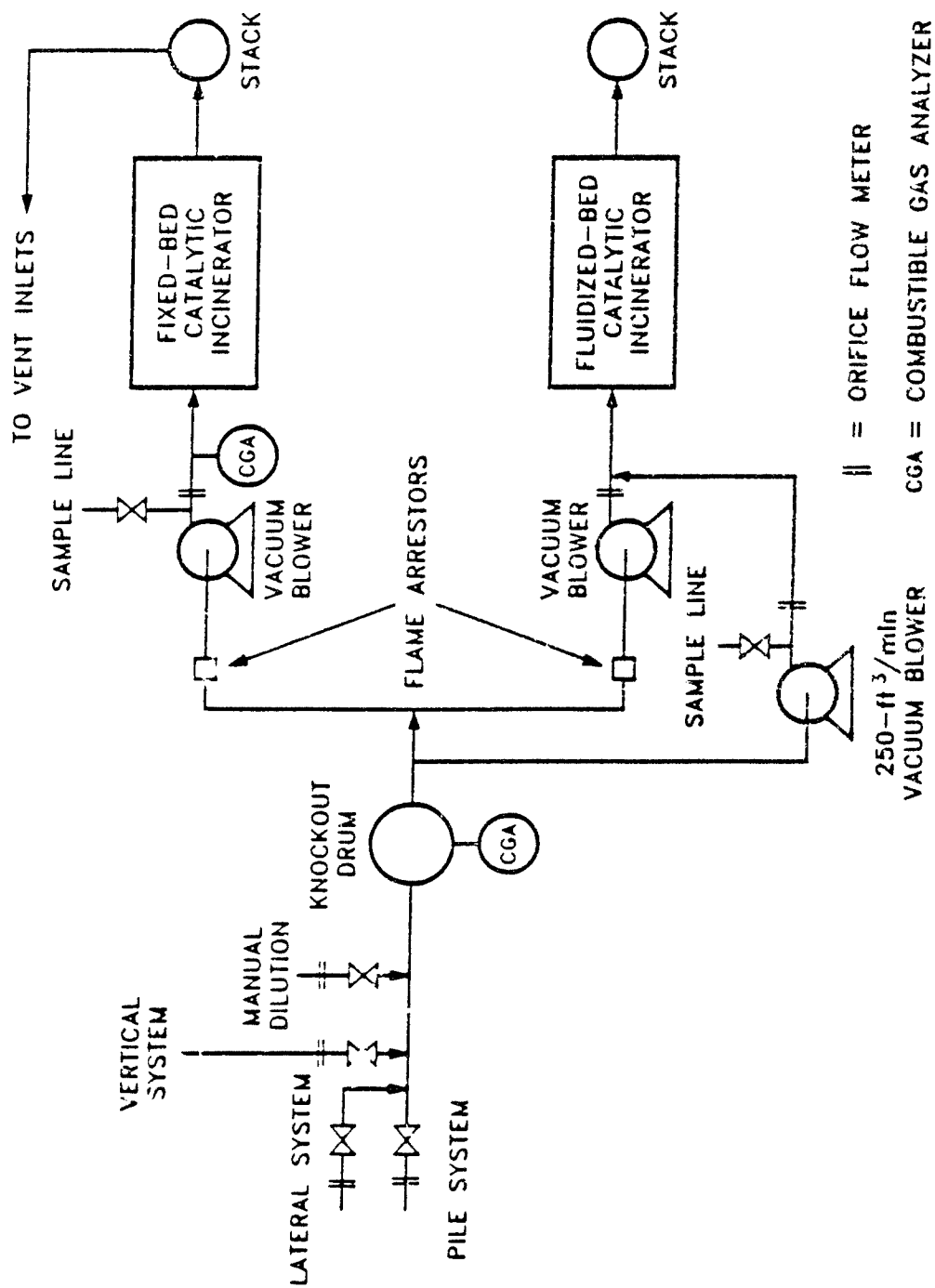


Figure 51. Schematic of Blower/Emission Control System.

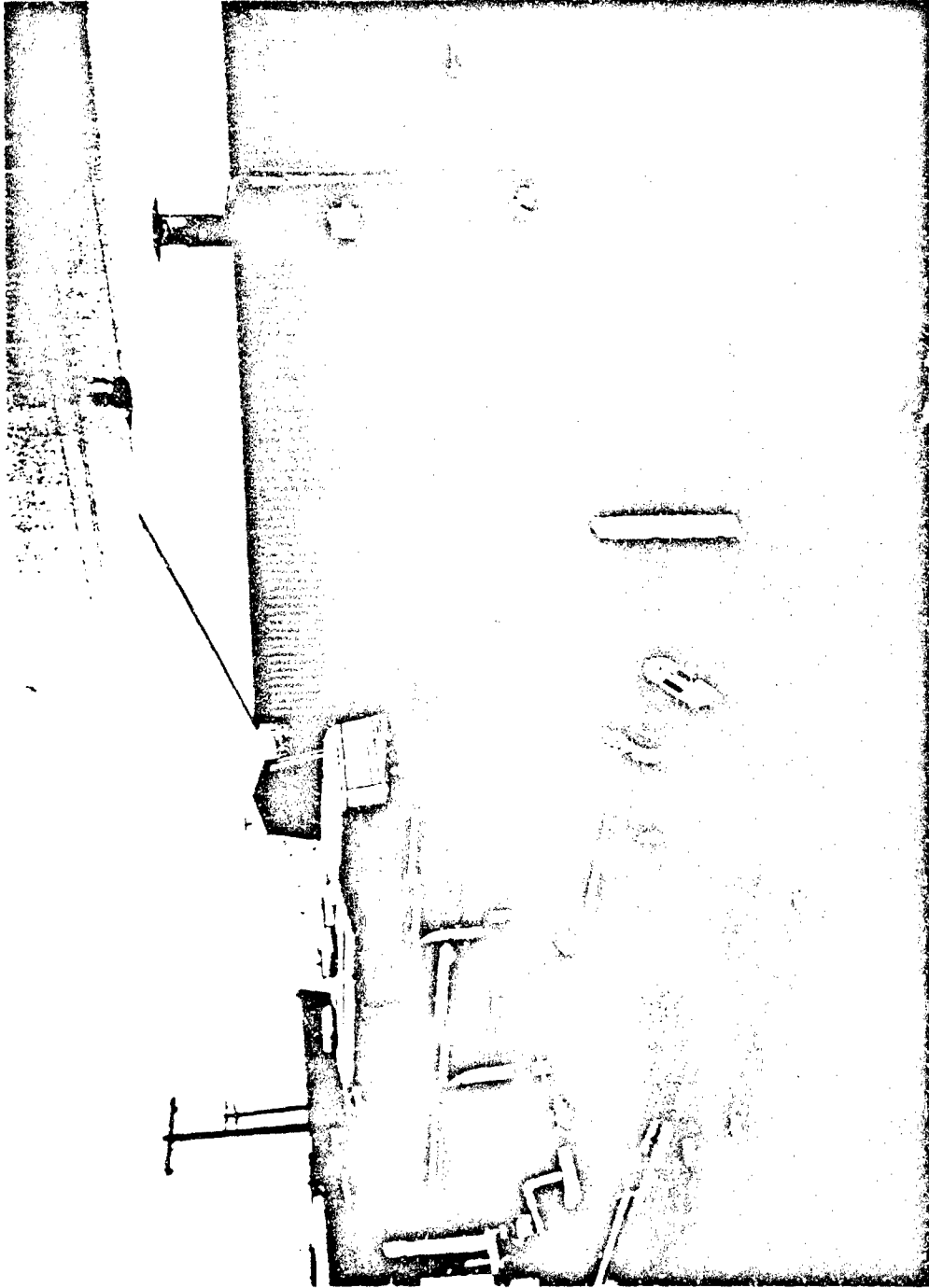


Figure 52. View of Blower/Emission Control System.

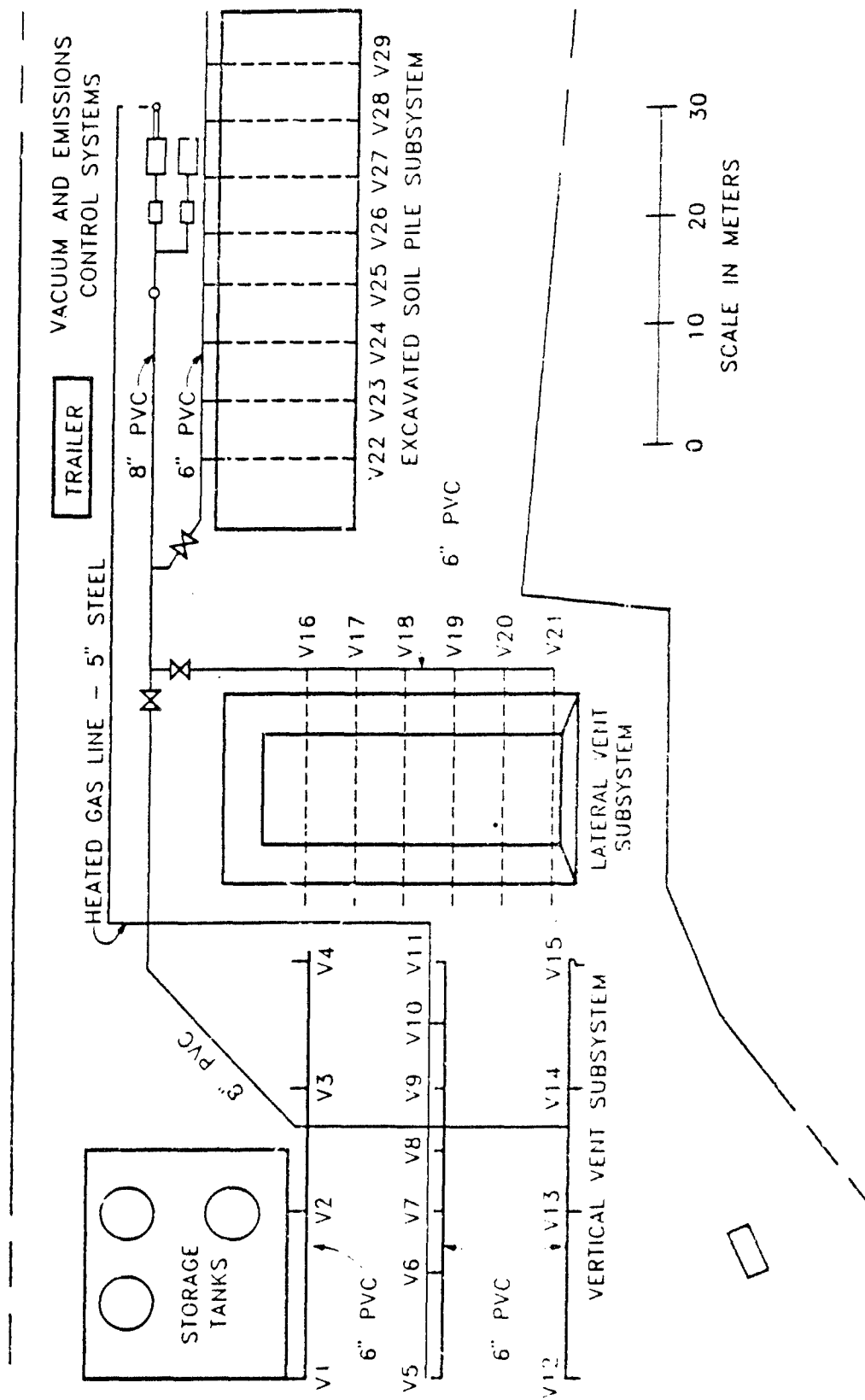


Figure 53. Piping Connecting Vents to Blower/Emission Control System.

gas stream. The knock-out drum was constructed from a 2-foot (61-cm) diameter x 7-foot (2.1-meter) tall cylindrical stainless steel tank. A 6-inch (15.2-cm) thick standard stainless steel wire mesh demister was used for removal of particles and coalescing of water droplets.

The insulated and heated-traced tank contained three explosion-proof level switches for management of liquid collected. The middle switch was used to activate a drain pump, which would shut off when liquid had fallen below the lower switch. Activation of the upper switch would indicate failure of the drainage system, and cause a relay to shut down power to the entire venting system. This tank drainage system was not used during the test due to very low water uptake.

#### d. Vacuum Blowers

Three rotary-lobe vacuum blowers, one capable of 250 scfm (0.12 standard m<sup>3</sup>/second) at approximately 100 inches of water (25,000 Pascals) vacuum and the other two each capable of 500 and 1000 scfm (0.24 and 0.47 standard m<sup>3</sup>/second) at 100 inches of water (25,000 Pascals) vacuum, were operated to extract gas from the vents. The smaller blower was used only during the start-up period, when elevated hydrocarbon concentrations were expected, and had spark-resistant aluminum lobes and housing with an explosion-proof 7.5 hp (5.6 kW) electric (460 volt, 3 phase) motor. The larger blowers were of conventional construction with weatherproof 30 hp (22 kW) electric (460 volt, 3 phase) motors. One of the larger blowers had a pulley ratio such that it would operate at a maximum flow rate of half of the other in order to match the design capacity of the smaller of the two catalytic oxidation units. Silencers were installed on the inlet and outlet of the blowers. Flame arrestors were installed in the lines prior to the blowers for protection in case of sparking.

#### e. Catalytic Oxidation Units

Two rental catalytic oxidation units, one of fixed catalyst bed design supplied by Engelhard Corporation and one with fluidized catalyst bed design supplied by ARI International, were used for destruction of the hydrocarbons in the gas stream. The reason for operation of the two types of oxidizers was to test the difference in operability and economy. Fluidized-bed units may be capable of more economical operation during early portions of soil venting operations due to their ability to handle a greater temperature rise across the mixed bed; however, a fluidized bed may be more expensive to run at low concentration and may require more maintenance.

The test units each consisted of a blower, propane-fired preheaters, catalytic reactor, and temperature, flow and pressure instrumentation. Each unit was skid mounted. Neither system included a heat exchanger for heat recovery.

Descriptions of each of the units, supplied by the vendors, are included in the following paragraphs.

##### (1) Fluidized Bed Unit\*

A schematic of the fluidized bed catalytic oxidation unit, an ARI Econ-Abator\* model rated for 500 scfm flow rate, is shown in Figure 54. The system components consists of a flanged

---

\*This section supplied by ARI International.

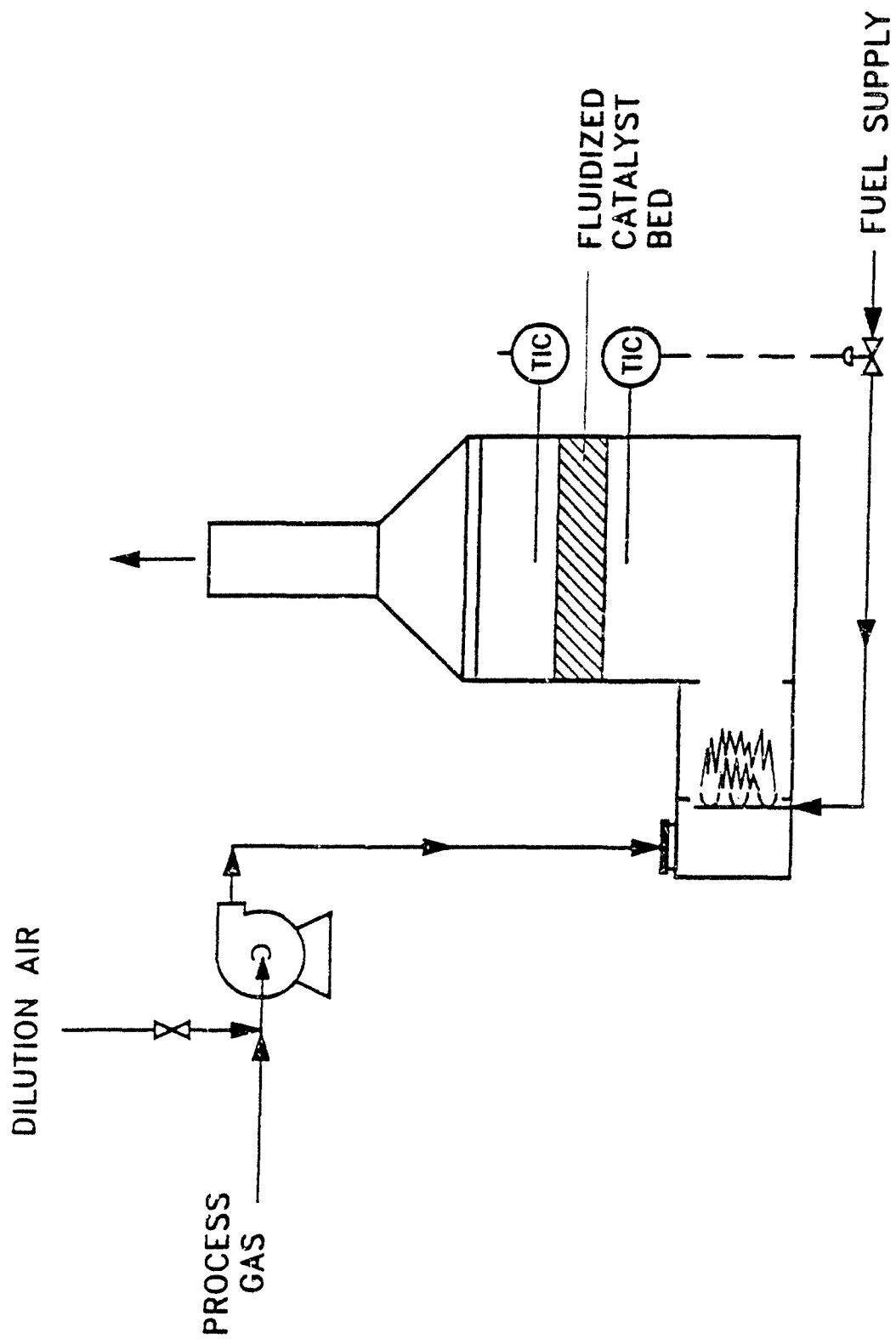


Figure 54. Fluidized Bed Catalytic Oxidizer (Redrawn from ARI International).

inlet, connecting ductwork, preheat burner chamber, combustion chamber, catalyst support and distribution grid, and 4-foot (1.2-meter) self-supporting discharge stack.

The process gases to be treated enter the system directly into the preheat burner chamber where they are raised to the required reaction temperature. The burner and controls are sized to preheat the gas stream to the design thermal oxidation temperature. The burner has a fixed-process flow turndown of 2.3 to 1, adjustable to 5 to 1 and a fuel turndown of 13 to 1, if required. All of the fume stream passes through the burner grid, assuring uniform mixing, heating, and distribution.

The fume stream next enters the combustion chamber where the fumes are oxidized to carbon dioxide and water. The combustion chamber consists of a rugged steel outer shell lined with a 1900° F (1040° C) insulating block. The chamber and components are designed for operation in the thermal as well as the catalytic mode, providing the user with complete operating flexibility. Insulating wall thickness allows for an outer shell temperature of 160° F (71° C) based on ambient conditions of 80° F (27° C) still air. The combustion chamber design provides residence times in excess of 1 second. The combustion chamber is equipped with thermocouple ports, test ports, observation ports, and two access doors. It is also equipped with a catalyst loading and a catalyst unloading system. The combustion chamber also contains a stainless steel catalyst support plate and distribution grid. This support provides the proper distribution of the fume stream and the correct catalyst fluidization, assuring uniform flow and complete contact of the fume stream with the catalyst.

The unit was supplied with a NEMA 4 control cabinet, completely tested, wired and bussed for 230/460-volt, three phase, 60-cycle power supply, and includes control transformer, ignition transformer, instrumentation, safety controls, disconnect, first-out detection system, alarm system, and all necessary fuses, pilot lights, push buttons, timers, relays and terminal blocks.

A Honeywell UDC-3000 electronic, position-proportioning 3-mode indicating temperature controller with Type K Megopak thermocouple and leadwire, is used to control the preheat burner and combustion chamber reaction temperature. A Honeywell UDC-2000 electronic, high-limit temperature indicating alarm with Type K Megopak thermocouple and leadwire, is used to provide excessive temperature protection. A Honeywell Modutrol position-proportioning control motor is used to operate the preheat burner fuel control valve and linkage.

The flame safety and control system is designated for indoor installation and to meet factory mutual (FM) insurance requirements for most areas. Standard options included design for Industrial Risk Insurers (IRI) requirements and outdoor installation. The flame safeguard system utilizes a Honeywell "ProtectoRelay" complete with pre-purge timer and pilot timer. A Honeywell "Ultravision" electronic flame detector is standard. All necessary gas pressure switches, air flow switches, solenoid valves, safety valves, block valves, gas pressure regulators, and pressure gauges are furnished for indoor installation.

## (2) Fixed Bed Unit\*\*

A schematic of the fixed bed catalytic oxidizer, a CSM Systems model rated for 1000 scfm flow rate, is shown in Figure 55.

The soil vent gas is isolated from the fixed bed catalytic oxidizer by a flame arrestor to prevent flash back. The control dampers are included to allow adjustment to keep the hydrocarbon concentration below 25 percent of the lower explosive limits. The gas blend enters the oxidizer at the 21-1/2 inch x 34-1/2 inch (54.6-cm x 87.6-cm) flange into the combustion chamber. The unit is equipped with a raw gas burner which provides heat to the exhaust stream. Either natural gas or propane can be used as burner fuel. For this project, propane was used as fuel. The temperature of the incoming gas blend is increased to the desired catalyst inlet temperature. The catalyst inlet temperature is controlled by a temperature controller located on the local control panel.

The preheated gas blend then passes through a filter/mixer section. This section is designed to improve flow and temperature distribution. It also serves to vaporize any aerosols that may have entered the system. Impurities are adsorbed on the ceramic elements used here and organic particles are destroyed by burning.

The gas blend then passes through two modules packed with catalyst where the hydrocarbons are oxidized to carbon dioxide and water. A catalyst module is illustrated in Figure 56. Each module contained 12-inch (30.5-cm) deep precious metal coated ceramic monolith. Both modules are sealed against the T-bar frame with fiberglass gaskets to prevent channeling around the modules. About 2 ft<sup>3</sup> (0.06 m<sup>3</sup>) of catalyst was installed. The cell density of the ceramic monolith was 200 cells/inch<sup>2</sup> (31 cells/cm<sup>2</sup>). A special proprietary mixture of precious metals was used for this application to obtain low operating temperature with high conversion of the JP-4 hydrocarbons.

The catalyst exit temperature is recorded on a multiple pen recorder. The clean exhaust is pulled through the system by the main blower and pushed into the stack. Waste heat from the stack gas would normally be recovered by heat exchange; however, in this application, heated air was either directed down the heat injection lines or discharged directly to the atmosphere.

Catalyst bed inlet and outlet temperature were used for control of heating within the units. Catalyst bed inlet temperature was used to adjust heat input from the preheaters. Catalyst bed temperature rise was used in conjunction with hydrocarbon concentration measurements to manually adjust dilution of the process gases.

Safety features in addition to the flame arrestor included a burner management system and a temperature activated relay to shut down the soil vent gas delivery system in case of high temperatures. A digital signal was available from each unit for switching a relay for shutdown of other process equipment in the event of an automatic shutdown. Automatic shutdowns would occur in the event of excessive temperature at any point in the unit, including the blower, an electrical heater surface, catalyst bed inlet or exit, or the stack, excessive pressure drop across the catalyst bed, or flame out.

---

\*\*This section provided by R. M. Yarrington, Engelhard Corporation.



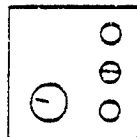
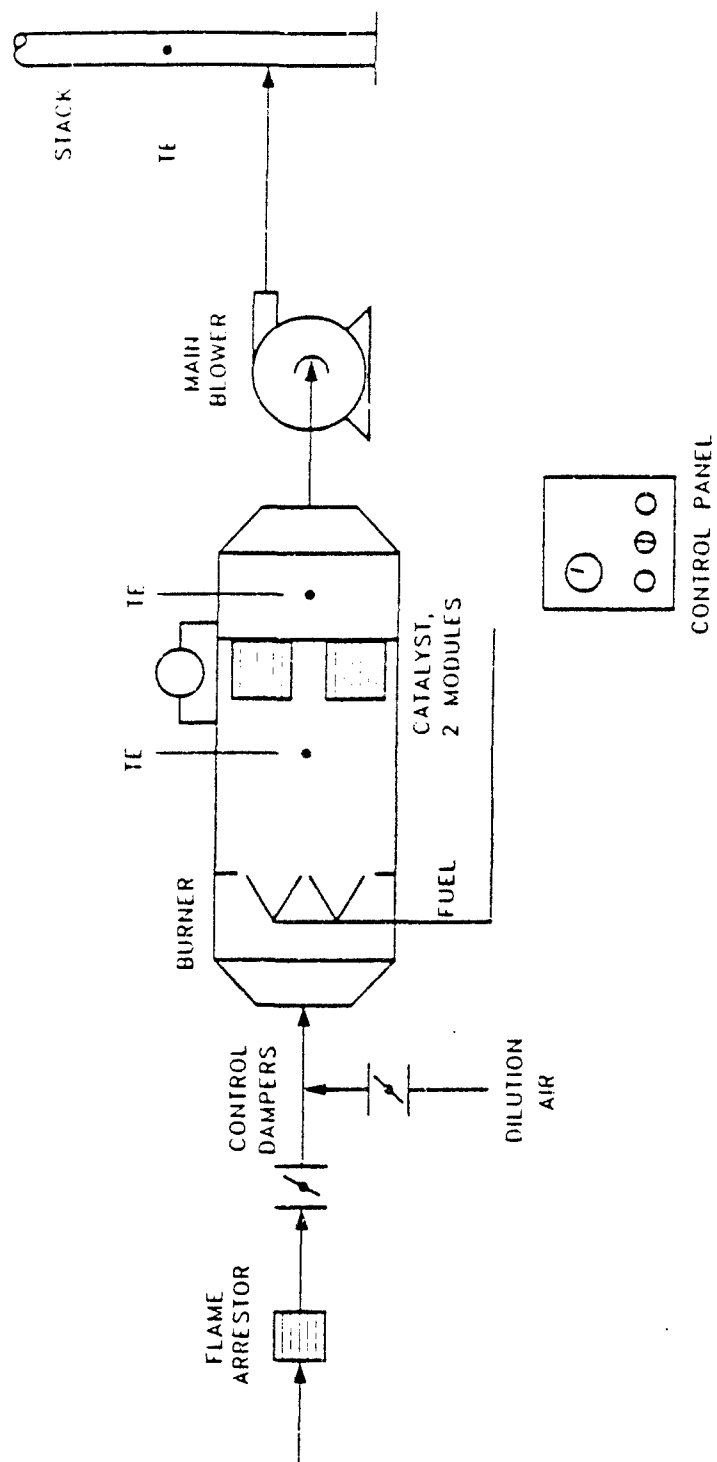


Figure 55. Fixed-Bed Catalytic Oxidizer (Redrawn from Engelhard Corporation).

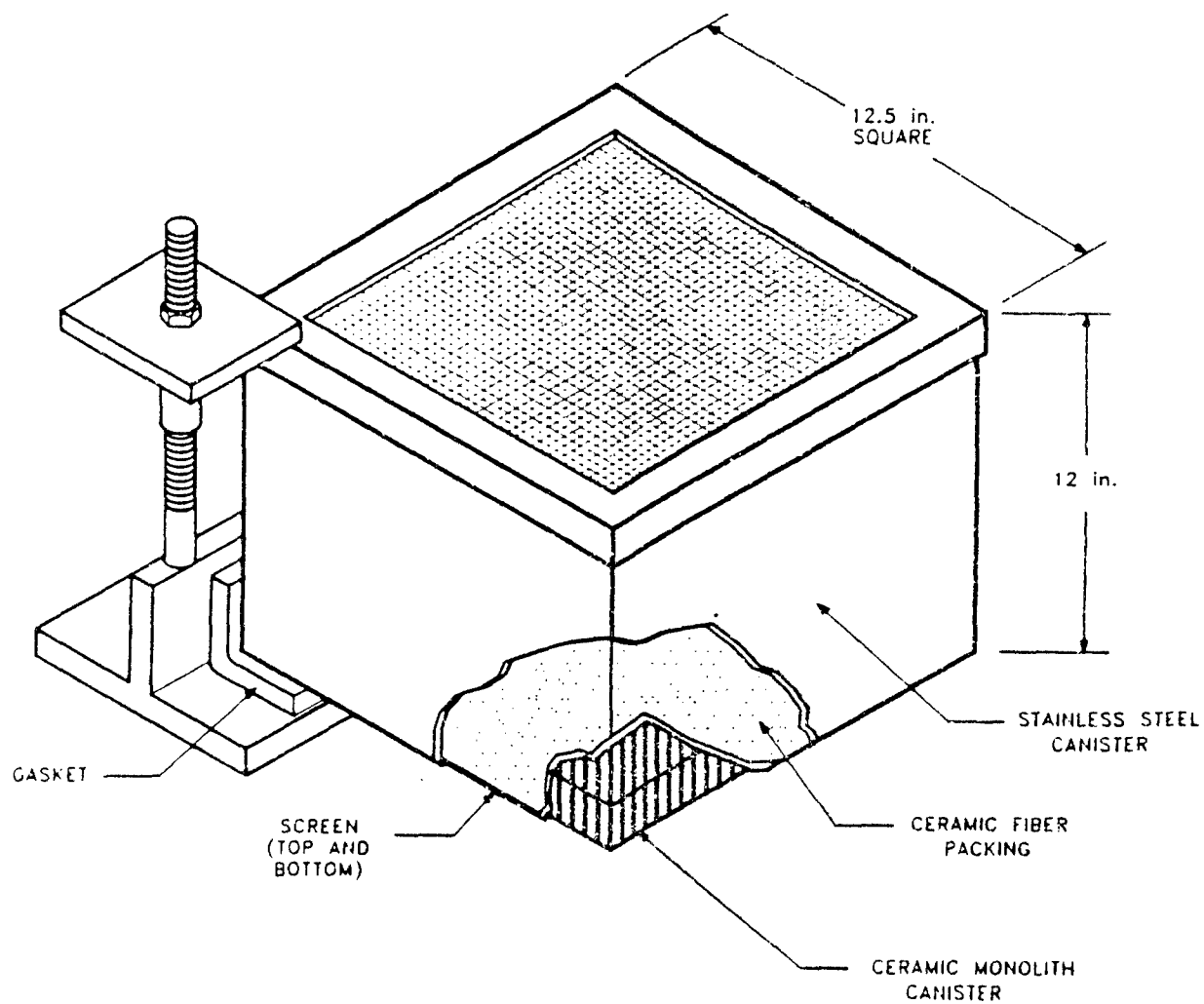


Figure 56. Fixed-Bed Incinerator Catalyst Module (Redrawn from Engelhard Corporation).

#### **f. Heat Injection Line**

A steel line was connected to the fixed-bed catalytic oxidizer stack for direction of the heated stack gas to the vents in the vertical vent subsystem. The 5-inch (12.7-cm) tubing was covered with 1 inch (2.54 cm) of fiberglass insulation and aluminum insulation wrap. The line had taps for connection of a hose to each end vent and had 4-inch (10.2-cm) steel tube connections to Vent 6 and Vent 10 (see Section V.B.1.e).

### **C. SYSTEM OPERATION**

#### **1. Modes of Operation**

The operation of the soil-venting demonstration may be broken into five activities: (1) start-up, (2) shutdowns for biological activity monitoring, (3) testing of vent configurations, (4) long-term operation, and (5) heat injection testing.

##### **a. Start-Up Period**

Beginning in mid-December 1988, Vent 7 of the vertical vent system was first vented using the 250-cfm blower previously used in the single-vent pilot test. Early operation of the soil venting system was performed using only the fluidized bed catalytic oxidizer for emissions control. The early operation period required careful attention due to the elevated hydrocarbon levels in the extracted soil gas, so the system was manned 24 hours a day. Extraction rates from the vents were kept very low initially, in order to dilute the extraction gas to the 500 scfm (0.24 standard m<sup>3</sup>/second) capacity of the oxidizer and remain within the maximum allowable temperature rise across the catalyst bed.

Initially, the feed to the preheated oxidizer was entirely from the main dilution valve and dilution valves at each vent head. The valve at the vent was then opened slowly, manually maintaining feed to the oxidizer at or below the design level of 25 percent LEL, as measured by the in-line combustible gas detector. The vent head dilution valves were closed slowly as the extracted gas concentrations fell. The main dilution valve was used to adjust concentration over most of the start-up period. Once it was ascertained that gas levels from the pile system were relatively low, the pile system gas was substituted for dilution air. When the concentration at the oxidizer inlet fell below 25 percent LEL, the system was operated without dilution. Hydrocarbon concentration in the extracted soil gas was also measured during the dilution stage by using the on-line Total Hydrocarbon Analyzer (THA) and the GC canister samples, as described in Section II.I.

Single-vent operation continued in a similar manner with extraction from Vents 9 and 10. Multiple-vent operation was initiated with the addition of the fixed-bed catalytic oxidizer and large blowers in early April.

##### **b. Shutdown for Monitoring of Biological Activity**

Although the measurements of CO<sub>2</sub> and O<sub>2</sub> in the extracted gas during venting operation provide much support for the aerobic biodegradation of hydrocarbons, further information could be obtained by the measurements of oxygen uptake in a static oxygen-rich state. For this purpose, AFESC contracted Battelle Columbus and Utah State University (USU) to perform evaluation of bioactivity at the Hill AFB site.

The venting operation schedule was altered to accommodate three periods of no venting activity. During these periods, ranging from 1 to 3 weeks in duration, no extraction was performed and measurements of CO<sub>2</sub> and O<sub>2</sub> were made at various monitoring points by USU personnel.

Results of the Battelle work are presented in Section V.E. along with further observations on bioactivity by ORNL.

#### **c. Testing of Vent Configurations**

After extraction gas concentrations had reached levels at which multiple vents could be run, flow tests involving several venting configurations were conducted at different times throughout the operation. The purpose of these venting configuration tests was to determine induced flow patterns for each configuration to measure the extent of "dead zones" — soil areas of high vacuum and low flow due to positioning between wells. Analysis of data from these venting configuration tests could help provide strategies for optimization of venting operation. Each venting configuration test was conducted by setting the flows at each vent, allowing the system to reach steady state, and reading vacuum levels at each of the vents and pressure monitoring points.

Vent configuration flow tests were conducted in the vertical and lateral systems only. In the vertical system, tests were conducted to determine flow patterns from single and various multiple vent configurations, both with and without a surface barrier. A limited number of tests were conducted including use of passive inlet vents. Lateral vent tests involved the operation of single and multiple vents, both with and without passive inlet vents. An overview of these tests is presented in Section V.G.

#### **d. Long-Term System Operation**

Long-term system operation began after extraction gas concentrations had decreased to the point that dilution of the feed to the catalytic oxidizer was no longer necessary.

The long-term operation was unmanned, with periodic monitoring by USU personnel. The transition to unmanned operation was made 20 April 1989 after smooth operation of the entire system including both catalytic oxidizers and large blowers had been demonstrated. The entire system was monitored at least twice per week with all system flow rates, pressures, temperatures, liquid levels and maintenance items checked. Samples of the extraction and effluent gas were taken for GC analyses during these system checks.

#### **e. Heat Injection Test**

In August 1989, the long-term operation was shifted from an extraction-only mode to extraction with a passive inlet vent. The passive inlet vent was connected to the stack of the fixed-bed catalytic oxidizer to allow the injection of heated gas into the soil.

Vents 9 and 11 were operated as extraction vents, and Vent 10 was opened to the stack gas. Temperature variations in the soil were monitored by thermocouples, and the extracted gas was continuously analyzed for total hydrocarbon concentration.

The heat injection test was conducted until the end of ORNL operation of the demonstration system in early October. Details of the test are presented in Section V.H.

## 2. Chronology of Operation

A detailed chronology of the full-scale system operation is presented in Table 14.

### D. RESULTS OF HYDROCARBON REMOVAL BY VOLATILIZATION

The results of hydrocarbon removal by volatilization in the Hill AFB demonstration may be displayed in terms of (1) mass removal as a function of time, (2) soil gas concentrations as a function of time, (3) extracted gas hydrocarbon concentration as a function of time, and (4) extracted gas composition as a function of time. Each of these subjects is discussed below.

#### 1. Mass Removal

The total amount of hydrocarbons removed was calculated as a function of time using the results obtained with the THA. These calculations are included in a spreadsheet in Appendix J (unpublished, available from ORNL and AFESC). The THA was calibrated with hexane; therefore the mass removal rate was calculated as the product of the concentration in the combined extracted gas streams, a conversion factor adjusting values in ppmv hexane equivalent to pounds of hexane per cubic foot of gas, and the flow rate in scfm. The non-linear response of the THA exhibited during the pilot tests did not affect the readings during the full-scale demonstration since the gas was diluted to below 25 percent LEL (3275 ppm hexane equivalent) in the stream leading to the oxidizers. The hydrocarbon removal values were integrated with time in the spreadsheet using the trapezoidal rule between data points. From these calculations, a total of 105,000 pounds (32,000 kg) of hydrocarbons were found to have been extracted over the period of the demonstration.

The results of these calculations are shown in Figure 57 in the form of cumulative hydrocarbon removal as a function of time, and in Figure 58 in the form of cumulative removal as a function of cumulative volume of gas extracted. This latter plot removes the effects of flow rate and down times on the shape of the curve. The results in these figures are typical of soil venting operations described in the literature, exhibiting high initial removal rates and asymptotically approaching an upper bound as venting progresses and concentrations decrease. The nearly constant initial (up to 70 days operation) removal rates as a function of time, as shown in Figure 57, are a result of the removal limitations set by the single emissions control unit. Horizontal portions of this curve indicate the shut-down periods allotted for testing of biological response. The period from 80-160 days displays a concave-upward curve, the result of shifting the operation from Vent 7 to Vent 10 at 83 days and greater flow capacity with the addition of larger blowers and the second emissions control unit. During the period from 175 days to the end of the demonstration, the operation was held relatively constant, with extraction from the same general area of the site (mainly Vents 9-11 and Vent 19). The only change during this period was a shift from approximately 1100 scfm to 800 scfm during the heat injection test from 16 August 89 to the end of the demonstration. This final portion of the curve (from 175 days to the end) displays the expected leveling of the removal curve.

The limit of the removal curve (within reasonable time limits) appears to be on the order of 110,000 to 120,000 pounds (50,000 to 54,000 kg), or 63 to 69 percent of the assumed 26,000-gallon

TABLE 14. DETAILED CHRONOLOGY OF FULL-SCALE SYSTEM OPERATION

DATE	ACTIVITY
18 December 1988	Extraction from Vent 7 for 25 hours. Fluidized bed oxidizer on line with 250-cfm blower.
19 December 1988	System shut down for evaluation of bioactivity in soil by Battelle.
6 January 1989	Vent system restarted with Vent 7 and small blower on-line.
13 January 1989	Oxidizer shut system down due to high hydrocarbon concentrations in vapor (high temperature shutdown). Oxidizer problems being worked out.
18 January 1989	Restarted extraction from Vent 7 using small blower.
20 January 1989	Shut down for catalyst replacement in fluidized bed oxidizer.
21 January 1989	Restart extraction from Vent 7 with small blower.
2 February 1989	Performed soil gas tests at each vent.
15 February 1989	Shut down for 9 hours for fluidized bed oxidizer insulation repair. Restarted extraction from Vent 7.
3-10 March 1989	System shut down for measurement of bioactivity by Battelle.
11 March 1989	Performed soil gas tests at each vent. Resumed extraction from Vent 10.
18 March 1989	Drained about 1 gallon (3.8 liters) of liquid condensate from main manifold line.
20 March 1989	Drained approximately 18 gallons (68 liters) of condensate from 6-inch (15-cm) manifold line between Vents 5 and 6. Added 12 gallons (45 liters) of catalyst to fluidized bed oxidizer.
28 March 1989	Fixed bed oxidizer delivered to site.
2 April 1989	Began extraction from Vents 9, 10, and 11 at 350 scfm (0.17 standard m <sup>3</sup> /second).
5 April 1989	Extraction from Vent 10 with pile gas for dilution air. (Small blower)
8 April 1989	Start-up of fixed bed oxidizer on-line with vent system.

TABLE 14. DETAILED CHRONOLOGY OF FULL-SCALE SYSTEM OPERATION  
(CONTINUED)

DATE	ACTIVITY
8 April 1989	Started extraction from Vent 9 with pile for dilution air. Both 1000-cfm blower and 250-cfm blower placed on-line. Both catalytic oxidizers operational.
11 April 1989	Extraction from Vent 7 and Pile.
13 April 1989	Started 500-cfm blower for feed to fluidized bed oxidizer.
13-21 April 1989	Performed several vent configuration flow tests by measuring steady-state vacuum at pressure-monitoring points during extraction from different vent combinations.
22 April 1989	Began extraction from Vents 9, 10, and 11.
15 May 1989	Began extraction from Vents 5, 6, 7, 8, 9, 10, and 11.
26 May - 10 June 1989	Shutdown test for measurement of bioactivity performed by USU and Battelle.
10 June 1989	Soil gas tests performed after 2-week shutdown.
10-19 June 1989	Gas extracted from Vents 5 through 11 (vertical) and Vent 19 of the lateral system.
19 June 1989	Closed Vent 5 to increase hydrocarbon concentration in extracted vapor.
22 June 1989	Closed Vents 6 and 7. Began extraction from Vents 8, 9, 10, 11, and 19 only.
10 August 1989	<i>In situ</i> soil-moisture content readings taken. Extraction from Vents 9, 10, 11, and 19.
11-15 August 1989	Installed heat injection piping to Vents 6 and 10.
13-15 August 1989	Ran various vents to get pressure readings at pressure-monitoring points.
16 August 1989	Started heat injection tests. Vents 9 and 11 operated as extraction vents. Vent 10 connected to heat injection line. (650 scfm extraction rate, 93 scfm inlet rate.)
21 September 1989	Drained 5 to 7 gallons (19 to 26 liters) of condensate from main manifold lines and 10 to 12 gallons (38 to 45 liters) from knock-out drum.

TABLE 14. DETAILED CHRONOLOGY OF FULL-SCALE SYSTEM OPERATION  
(CONCLUDED)

DATE	ACTIVITY
9 October 1989	ORNL operation of soil venting terminated. Soil gas tests performed at each vent after 21-hour shutdown.
12 October 1989	Soil sampling of the pile, water sampling of RST-1, and neutron access tube readings taken.
30 October - 6 November 1989	Soil samples taken from vertical vent area for postventing analysis.

(174,000-pound) initial spill volume. The discrepancy is due to biodegradation, volatilization prior to venting, and residual hydrocarbons. A portion of this residual amount of heavy hydrocarbons will not be readily removed by volatilization. Unless the remediation may be terminated because the soil falls within total hydrocarbon concentration limits or because of decreased risk assessment, an additional technique (such as bioremediation or heat enhancement) must be used for additional removal.

## 2. Soil Gas Concentrations

The progress of the venting system toward decontaminating the site may be shown most graphically by contour plots of the soil gas concentrations. These results, obtained from measurements made periodically during the demonstration, may be obtained relatively quickly, inexpensively, and with little disruption of the venting operation. Although they must be interpreted with care in cases of complex geohydrology (particularly in regard to confining layers in the soil), the results do not suffer from the great variability common to soil sampling and analysis.

Figures 59 through 64 show contours of the depth-averaged soil gas concentration expressed in units of parts-per-million hexane equivalent as a function of position. The data for these plots were obtained by extracting gas from each individual vent at rates up to 500 scfm for 5 to 10 minutes and noting the readings of the combustible gas detector (for the high levels of Figures 59, 60, and 61) and the THA. Therefore, the plots indicate the soil gas hydrocarbon concentration at a particular x-y position, integrated over the screened interval of the vents. The axes on the plots indicate feet in the N-S (y) and E-W (x) directions, the asterisks denote vent positions, and the numbers above the asterisks refer to the actual hydrocarbon concentration measurement for each well.

The hydrocarbon concentration contours of 2 February 1989 (after approximately one month of low-flow extraction from Vent 7) qualitatively match the soil concentration contours (see Figure 59). That is, higher levels existed in the vicinity of Vents 9, 10, and 11 with decreasing levels in a westward direction.



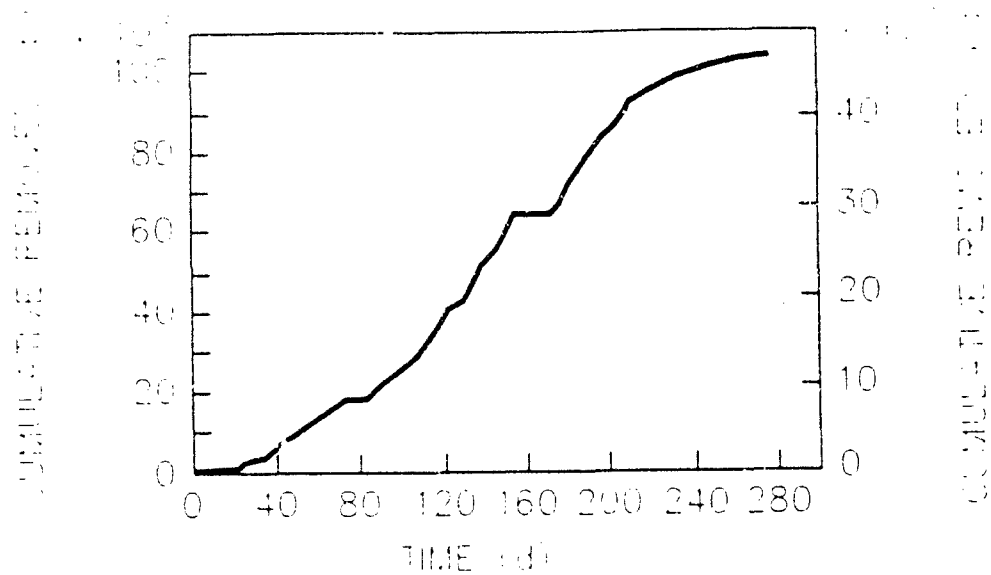


Figure 57. Hydrocarbon Removal by Volatilization - Cumulative Removal as a Function of Time.

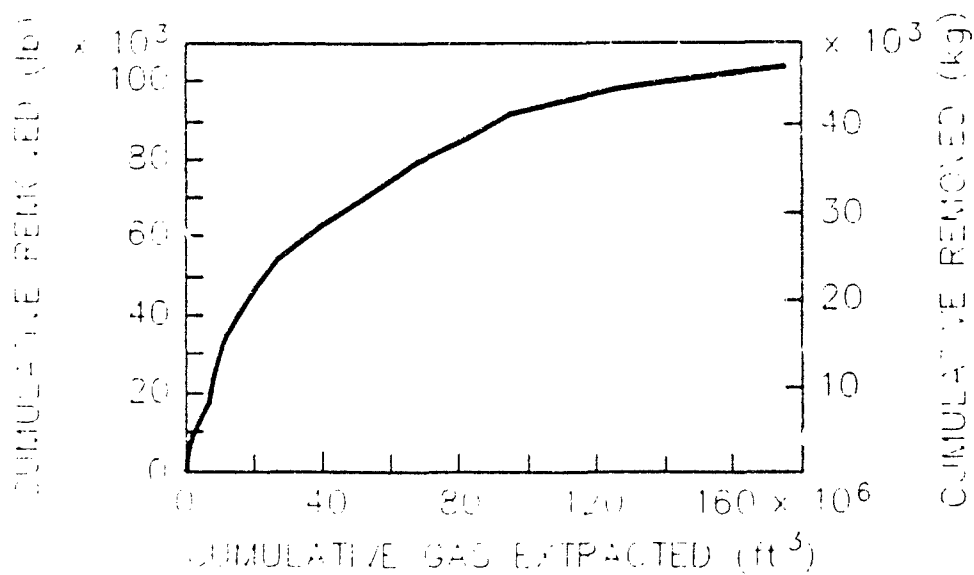


Figure 58. Hydrocarbon Removal by Volatilization - Cumulative Removal as a Function of Cumulative Gas Volume Extracted.

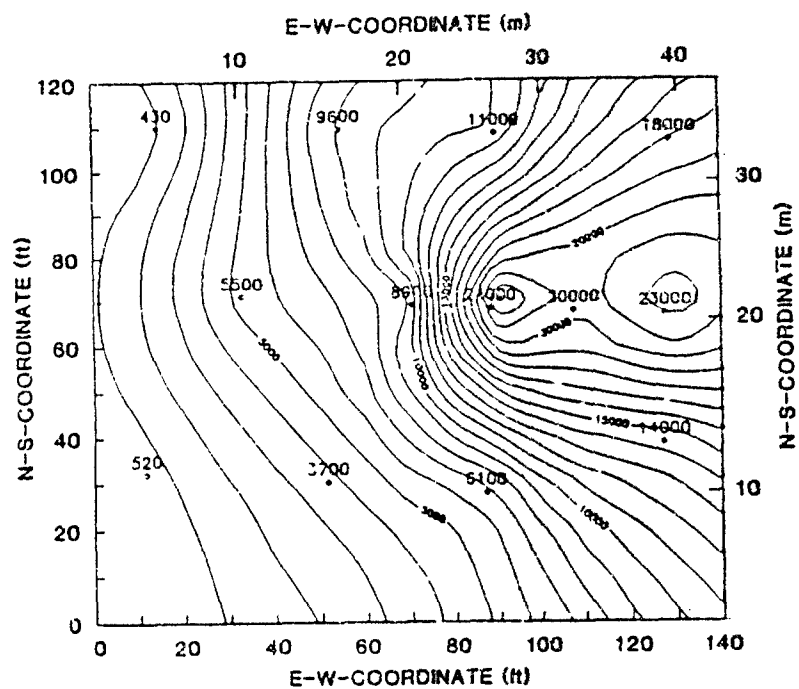


Figure 59. Soil Gas Hydrocarbon Contours (ppmv) - 2 February 1989.

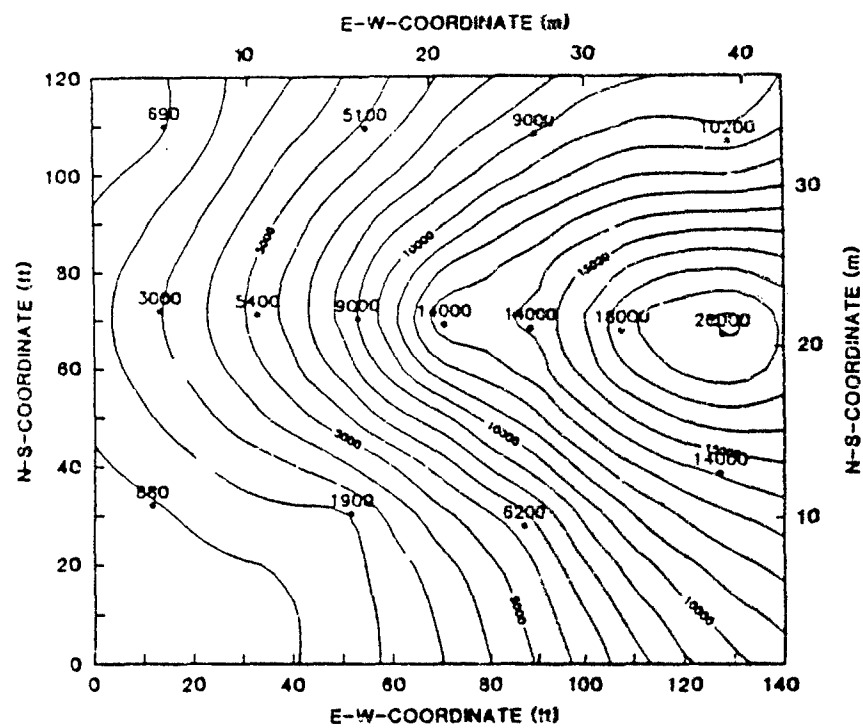


Figure 60. Soil Gas Hydrocarbon Contours (ppmv) - 3 March 1989.

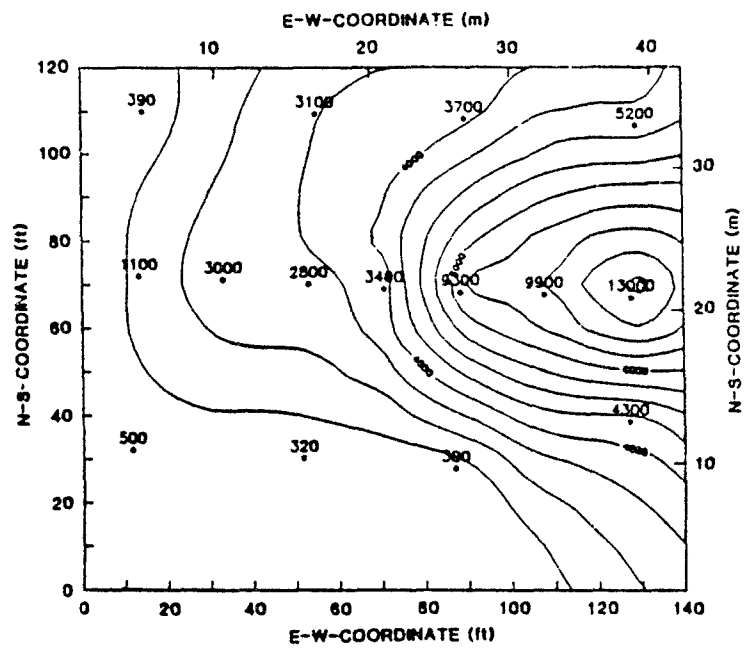


Figure 61. Soil Gas Hydrocarbon Contours (ppmv) - 2 April 1989.

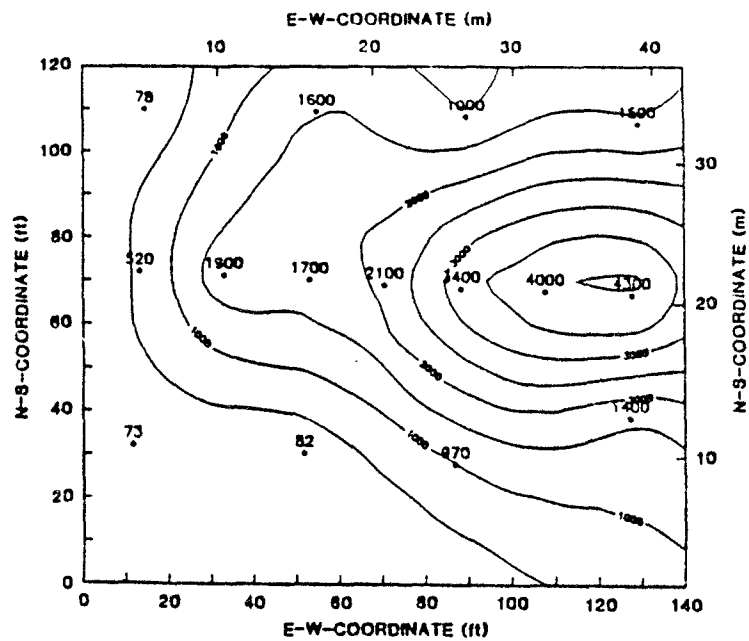


Figure 62. Soil Gas Hydrocarbon Contours (ppmv) - 10 June 1989.

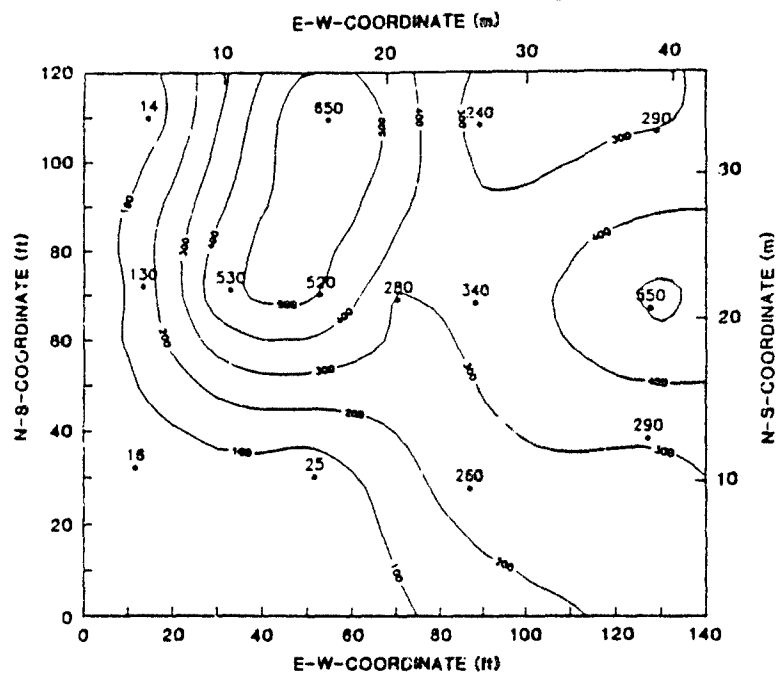


Figure 63. Soil Gas Hydrocarbon Contours (ppmv) - 12 August 1989.

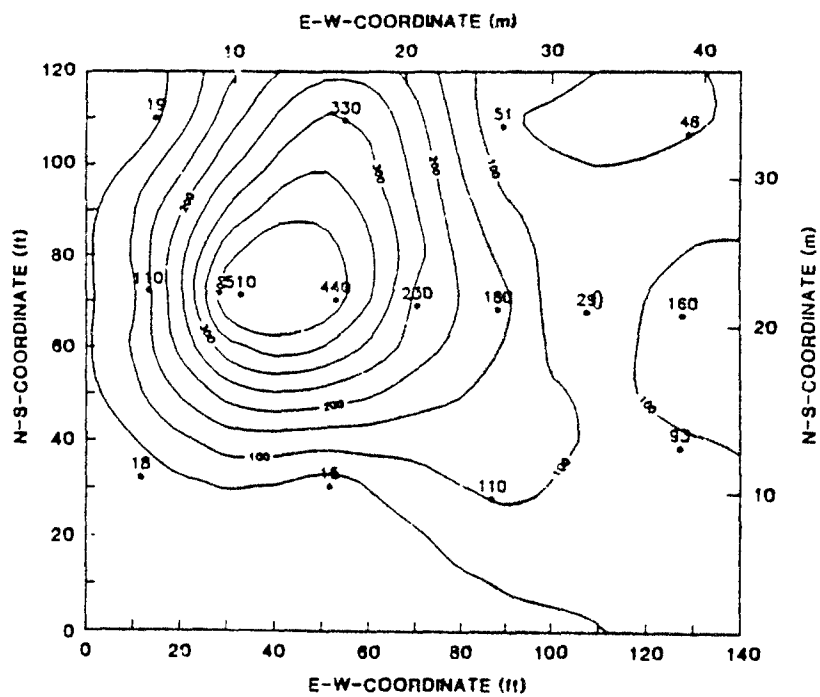


Figure 64. Soil Gas Hydrocarbon Contours (ppmv) - 7 October 1989.

Operation from 2 February 1989 to 11 March 1989 was mainly with extraction from Vent 7. Comparison of the contour plots for these dates qualitatively show a "pulling" of vapors from the more highly contaminated eastern region toward Vent 7 (see Figure 60). The area in the vicinity of Vent 7 does not appear to have been cleaned. Rather, removal from the fringes is suggested, as would be expected if equilibrium is reached throughout the soil (a reasonable assumption, especially in the low flow zones far from the extraction vent).

From 11 March 1989 to 2 April 1989, single-vent extraction was conducted with Vent 9 and Vent 10 (see Figure 61). In comparison of the plots for these dates, one can see a definite decrease throughout the system, but also a qualitative "pulling" of the contaminants from the fringes, as exhibited by greater relative decreases in concentration on the western edge. During this period, a single vent (either V9 or V10) operating at flow rates of up to 250 scfm was affecting the entire site and causing a lowering of soil gas concentrations relatively far [80 feet (24.4 meters)] from the vent.

From 2 April 1989 to 26 May 1989 extraction flow rate was increased to 350-500 scfm (0.17 to 0.24 standard meters<sup>3</sup>/second) (see Figure 62) and the center E-W line of vents was operated. As can be seen, a general decrease in concentrations occurred, with the relative shape of the contours being essentially unchanged.

From 10 June 1989 to 12 August 1989, Vents 9, 10, 11, and Vent 19 of the lateral vent system were operated at a total rate of 1100 scfm (0.52 standard meters<sup>3</sup>/second) (see Figure 63). There was a great decrease in soil gas concentrations in the entire eastern portion of the vertical venting system during this period. The western portion, although also obviously affected, did not exhibit as large a concentration decrease as would be expected due to the lower gas flow rates farther from the operating extraction vents.

From 12 August 1989 to 7 October 1989, the heat injection test was performed with extraction from Vents 9 and 11 and passive injection of heated air into Vent 10 (see Figure 64). The total extraction flow rate was 650 scfm (0.31 standard m<sup>3</sup>/second). During the heat injection test, the western half of the venting area was practically unaffected, whereas the eastern portion was effectively treated. Particularly notable is Vent 10, the hot air inlet vent, which reached an extracted gas hydrocarbon concentration of only 29 ppm hexane equivalent on re-equilibration. The operation with injection air, coupled with the fact that the surface of the eastern side was covered with a barrier and the western side was not, caused little treatment of the western half of the area during this period.

The soil gas results show that by operation of Vents 9, 10, 11 and 19 during most of the demonstration, the eastern portion of the vertical vent area was transformed from the most concentrated to least concentrated soil zone. These results, which are in qualitative agreement with the soil sampling results (see Section V.J), indicate that soil gas analysis is valuable for evaluation of venting progress, and would be particularly useful for guidance of system operation.

These results also support the installation of more extraction vents than might be initially deemed necessary at a site. Based upon initial soil sampling, it would be likely that extraction vents would not have been placed in the positions of Vents 2 and/or 6, since these areas were of relatively low concentrations. The above results have shown a shift in relative concentration toward these vents. Operation of Vents 2, 6, or 7 would provide greatest removal rates at the end of the demonstration.

### 3. Extracted Gas Hydrocarbon Concentration

Figure 65 displays the extracted gas hydrocarbon concentration measurements as a function of the cumulative gas volume extracted. This figure presents the THA results and the hydrocarbon concentrations determined by GC analysis of canister samples taken from the combined extracted gas stream. The GC results were converted to ppm hexane equivalent by assuming a constant weight response factor. Greater variation is noted in the grab sample results than from the on-line analyzer, as would be expected. Although reasonable agreement between the two measurement techniques is seen in the early operating period when highest concentrations were measured, the GC results are consistently lower than those from the THA for samples taken after approximately 500,000 standard  $m^3$  of gas extracted. This is thought to be due mainly to a combination of factors: (1) the assumption of a mean response factor for conversion of GC and THA detector response to total hydrocarbon concentration, and (2) losses or sorption on GC sample canister walls may also have occurred. The extracted gas hydrocarbon concentrations (as measured by the THA) decreased quickly from initial levels of about 45,000 ppm hexane equivalent (173,000 mg/liter) to approximately 6,000 ppm (23,000 mg/liter) after extraction of about 6.5 million scf (180,000 standard  $m^3$ ) from Vent 7. After switching operation to Vent 10, the extracted gas concentration dropped from about 22,000 ppm hexane equivalent (86,000 mg/liter) to 9,000 ppm hexane equivalent (35,000 mg/liter) during extraction of an additional 4.5 million scf (125,000 standard  $m^3$ ) of gas. The rest of the data points were obtained during extraction from several different combination of vents, mostly Vents 9, 10, and 11. Concentrations declined to a combined-stream concentration from Vents 9 and 11 of about 350 ppm hexane equivalent (1340 mg/liter).

Two ways of plotting data for extrapolation of performance that have been successful in some cases are semilog and logarithmic representations of concentration versus cumulative extracted gas volume. (Refer to Volume I.) These plots are shown in Figures 66 and 67. The logarithmic plot is especially valuable in examining the early periods of venting in which the most rapid changes occur. Two discontinuities of interest are highlighted by this plot. The first is an abrupt decrease in concentration from about 40,000 to 45,000 ppm hexane equivalent to about 25,000 to 30,000 ppm hexane equivalent, which occurred during a two-week shutdown after about 42,000  $ft^3$  (1200  $m^3$ ) of gas had been extracted. This decrease is similar to a concentration decrease that was measured after approximately 50,000  $ft^3$  (1400 standard  $m^3$ ) of gas was extracted during the pilot test. Some of this decrease may be due to uncertainty in concentration values at the high dilution ratios used during the high concentration period and to possible calibration problems during that same time as a result of condensation of hexane in the standard cylinder. However, it is believed that the break in concentration was primarily the result of the first pore volume of gas within the zone of influence being removed. Once the equilibrated light fractions in the vapor are removed, further extraction is caused by volatilization. The second discontinuity marks the point at which single-vent extraction was shifted from Vent 7 to Vent 10. The concentration increase was due to the fact that the latter vent was positioned nearer the center of the most highly contaminated zone, and in an area which had been contacted by less gas flow than the area around Vent 7. Neither of the two representations resulted in a straight line, as would be desirable for ease in extrapolation of behavior to predict performance. This is not surprising, given the complex interaction of air flow/contaminant geometry and contaminant fate mechanisms controlling the behavior. The semi-log plot is reasonably represented by a straight line beyond the point of 20 million  $ft^3$  (550,000 standard  $m^3$ ) of gas extracted. This line may be valuable for empirical extrapolation of the performance of the system. However, the point after which a linear fit would no longer be reasonable, if such a point exists, would need to be determined. Such a point may be indicative of a situation where free hydrocarbon

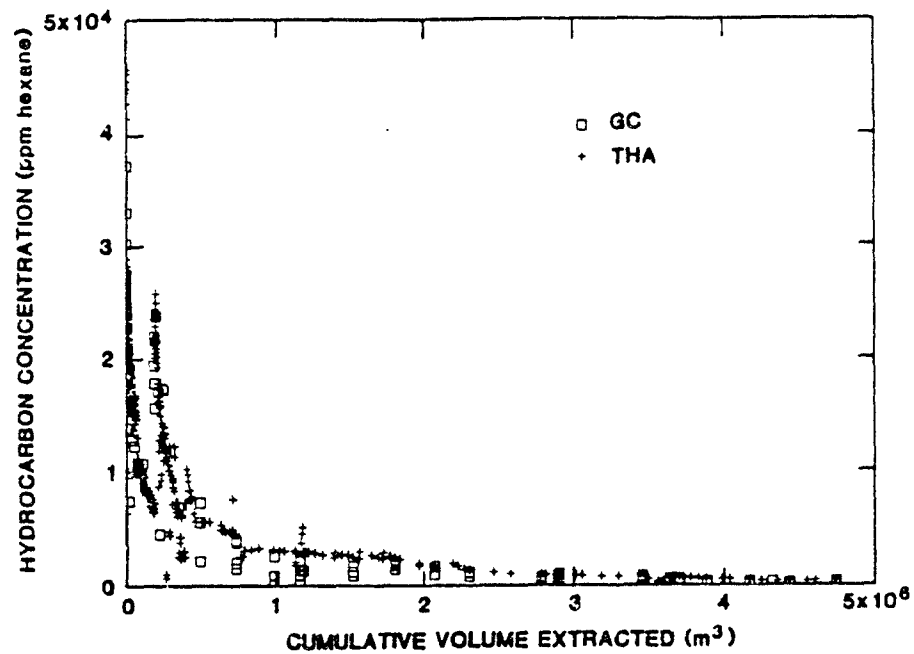


Figure 65. Variation of Hydrocarbon Concentration - THA and GC Samples.

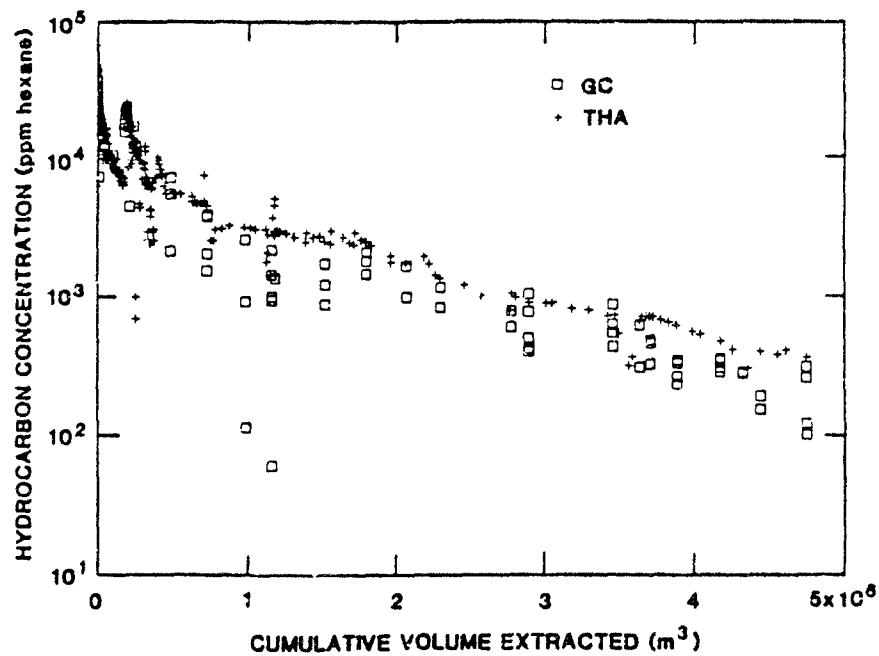


Figure 66. Variation of Hydrocarbon Concentration in THA and GC Samples, Semi-Log Representation.

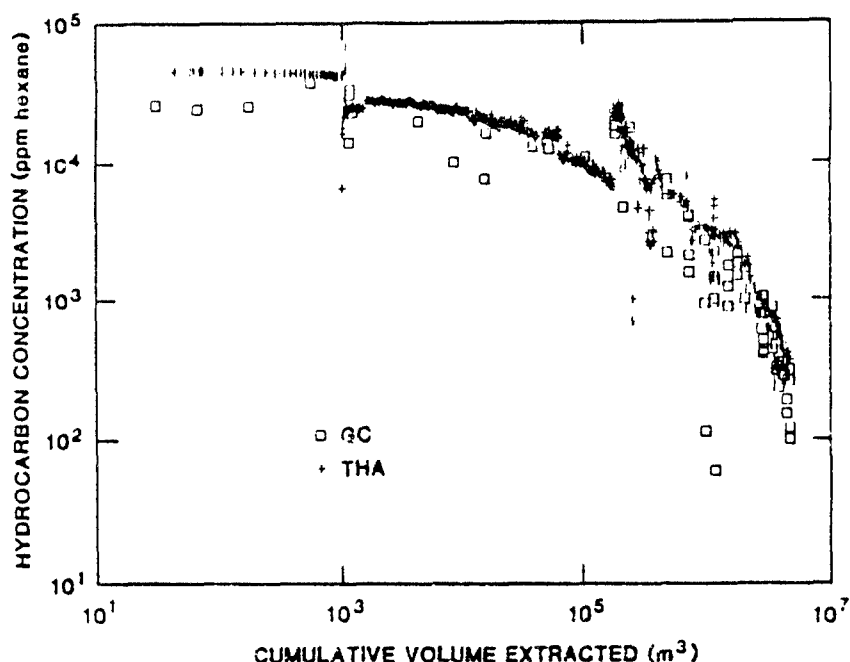


Figure 67. Variation of Hydrocarbon Concentration in THA and GC Samples, Logarithmic Representation.

films are no longer present as a separate phase and the soil shifts from a four-phase to a three-phase system (vapor, aqueous phase, and solid), as indicated in the modelling work of Johnson, et al. (Reference 17). There does not seem to be a reliable means by which to check this hypothesis from this field study.

#### 4. Extracted Gas Hydrocarbon Distribution

As has been shown by several investigators, as early as Thornton and Wootan (Reference 15), the composition of the hydrocarbons in the soil and in the extracted gas will shift toward a heavier mixture as venting progresses. The trend is strikingly displayed in Figures 68, 59, 70, and 71 which present gas chromatograms of representative samples throughout the demonstration. The X-axis of these plots represents the retention time, which generally corresponds to volatility of compounds, with less volatile compounds registering later. Several common compounds are identified in the plots. The y-axis indicates voltage measurements made by the FID detector of the instrument, which are proportional to concentration of compounds. Comparison of the plots indicates a pronounced shift toward heavier constituents in the extracted gas. One may also note that the voltage readings of the peaks decreased, corresponding to the drop in hydrocarbon concentration. Appendix C presents all measurements of hydrocarbon composition made during the demonstration.



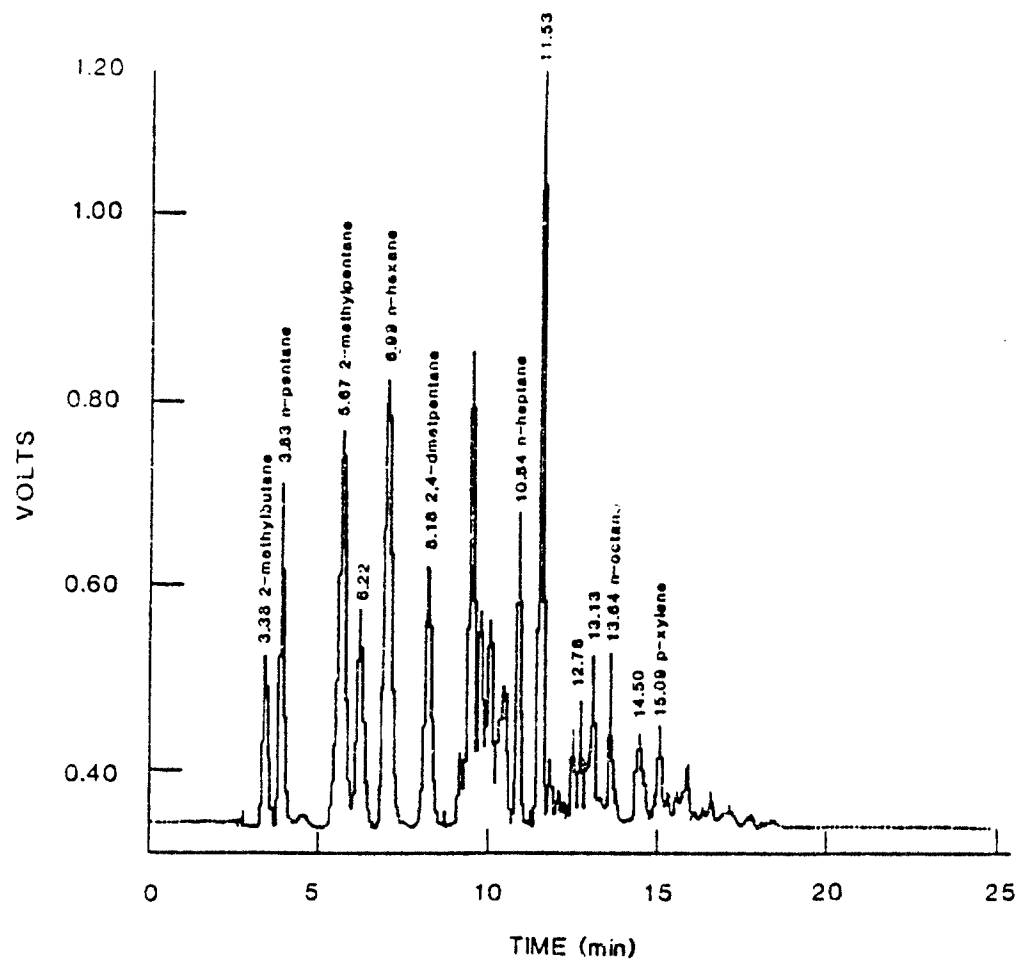


Figure 68. Gas Chromatogram of Extracted Gas Sample, 6 Jan 1989.

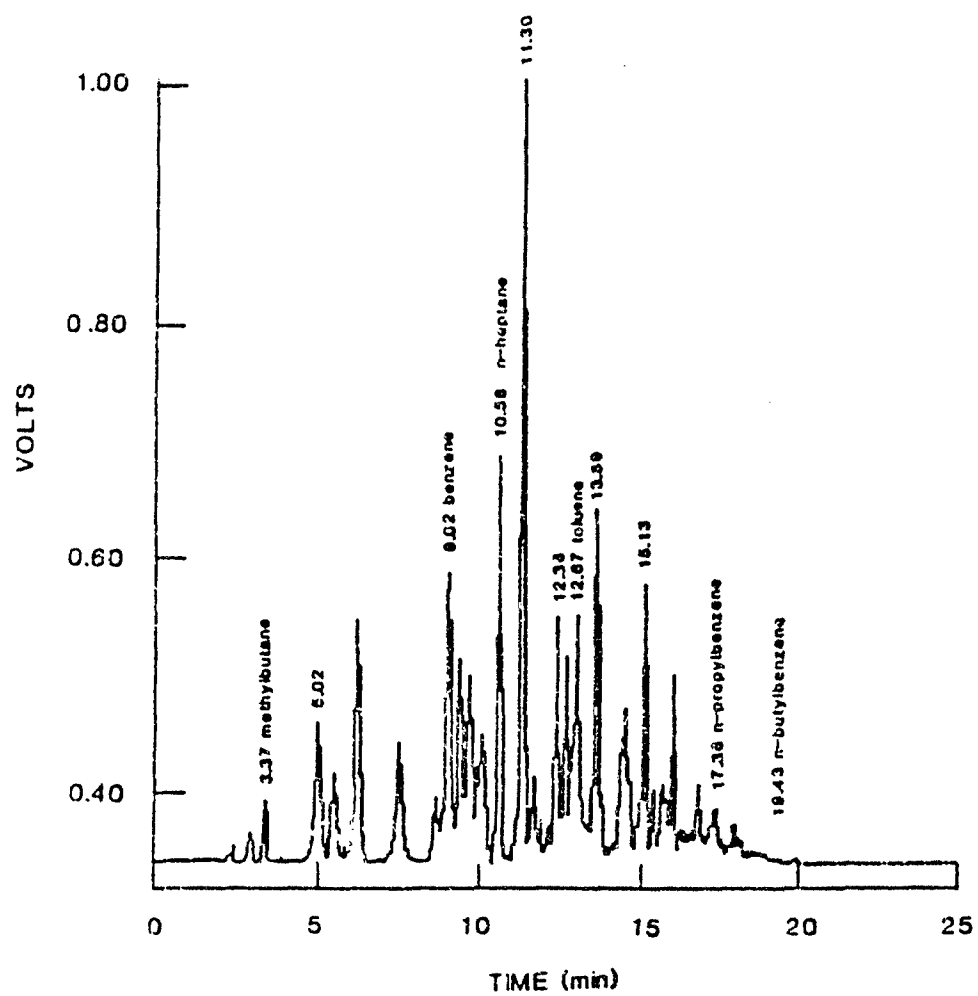


Figure 69. Gas Chromatogram of Extracted Gas Sample, 1 Mar 1989.

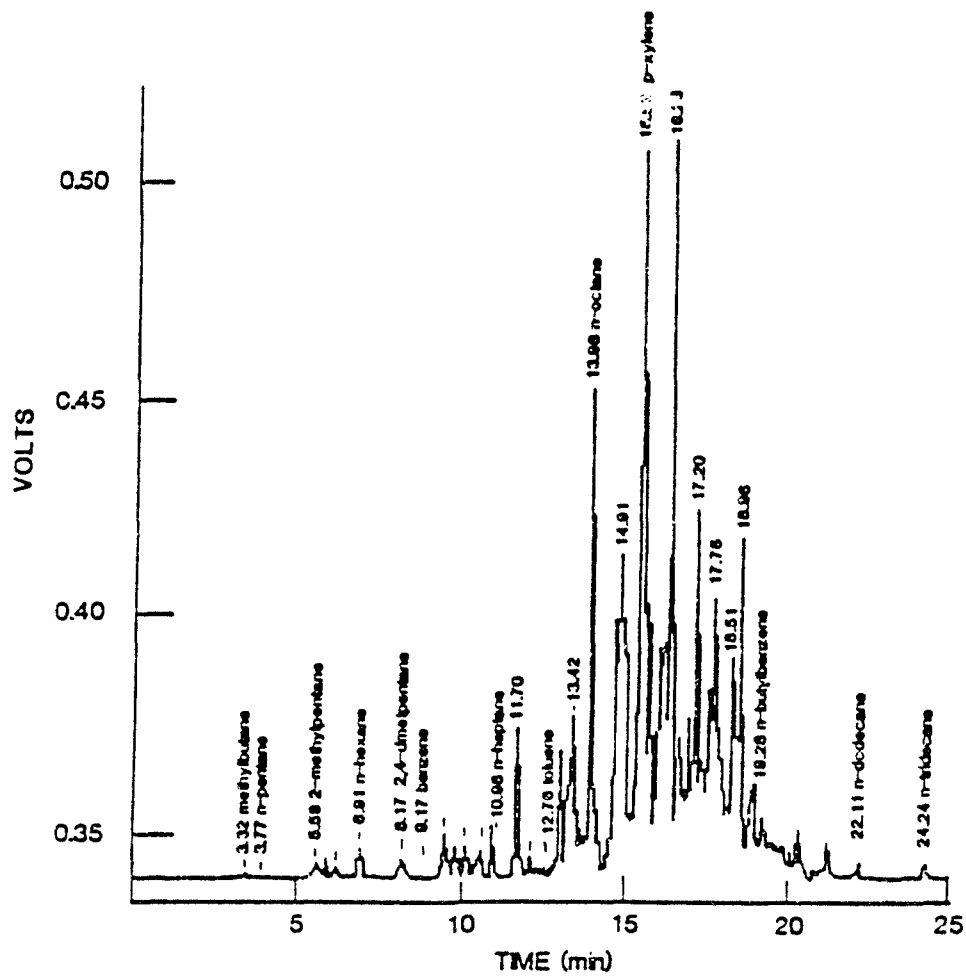


Figure 70. Gas Chromatogram of Extracted Gas Sample, 26 May 1989.

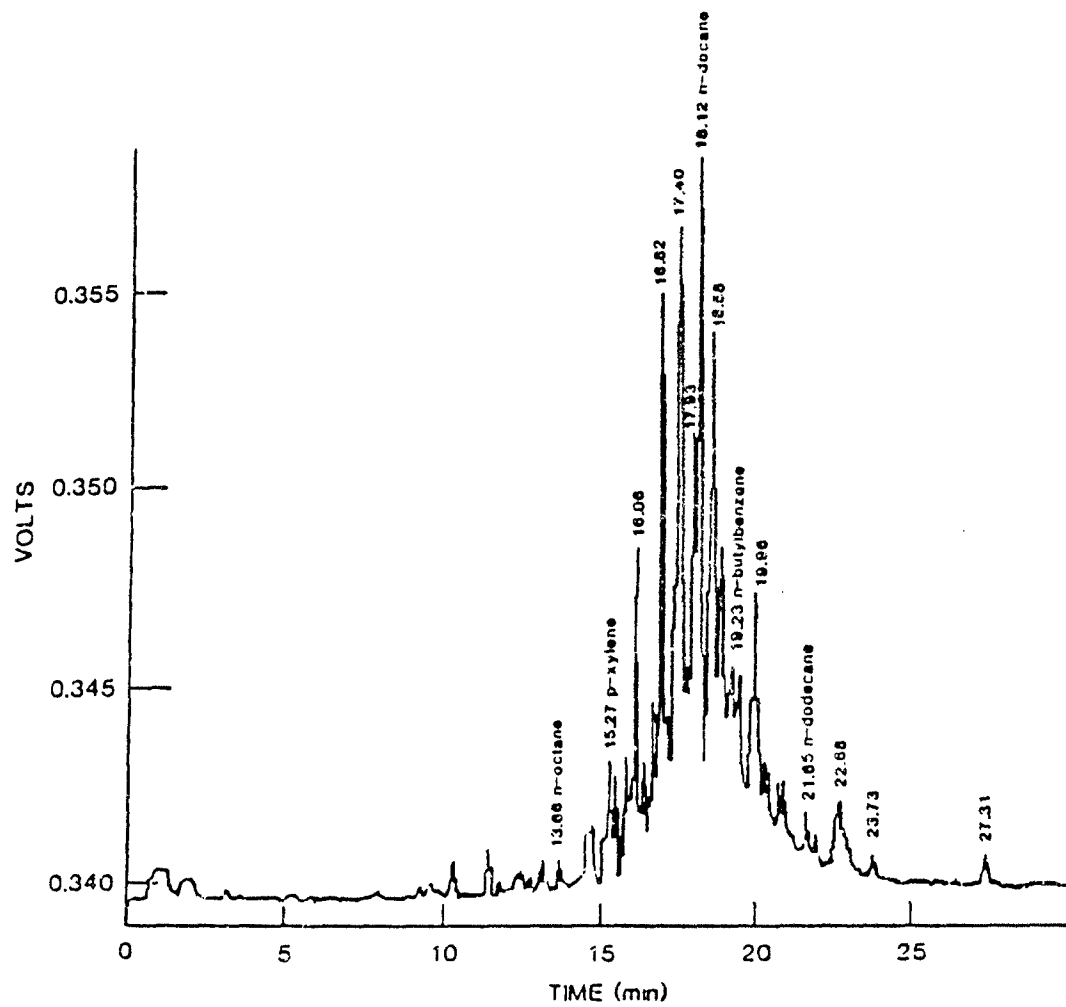


Figure 71. Gas Chromatogram of Extracted Gas Sample, 21 Aug 1989.

Figure 72 shows a bar chart of the relative weights of each hydrocarbon fraction (as defined by number of carbon atoms per molecule) in samples taken from the combined extracted gas stream throughout the operation. In this plot, the more volatile fractions are removed first, enriching the extracted gas (and remaining hydrocarbons in the soil) in the heavier compounds.

### 5. Comparison with Equilibrium Model

The results of this demonstration were compared with a simple equilibrium model to test the equilibrium assumption shown by Marley and Hoag (Reference 16) to be valid for description of venting of gasoline in a bench-scale column. Johnson et al. (Reference 17) suggested this model for projecting removal behavior of full-scale systems.

In this case, an idealized model based on Raoult's Law was used. Raoult's Law was chosen over Henry's Law due to the low moisture content, relatively high hydrocarbon concentrations in the soil, and the low aqueous solubility of most JP-4 components. Henry's Law is valid for vapor-liquid equilibrium of one component at infinite dilution in another, as would be the case for hydrocarbons in aqueous solution, whereas Raoult's Law describes vapor-liquid equilibrium for an ideal solution of components, as is approximated by a mixture of similar hydrocarbons in a non-aqueous phase. This model assumes vapor-liquid equilibrium between the hydrocarbon phase and the soil gas, and perfect contact between the hydrocarbon contaminants in the soil and the soil gas at every point. Therefore, no diffusional resistances to removal are included, and equilibrium dictates the magnitude of hydrocarbon removal rate by the convective flow of soil gas. Using these assumptions, the entire contaminant mass can be considered to be in contact with the entire gas flow in one equilibrium stage. [More complicated models could be foreseen with several equilibrium stages, allowing calculation of spatial variation of removal, similar to the two-dimensional Henry's Law-based model presented by Wilson et al. (Reference 18)].

This model assumes removal by volatilization only, ignoring the effects of biodegradation, aqueous solubility, and volatilization from an aqueous phase or sorption on soil particles. These effects were included in the model of Reference 17. Addition of these factors would not be difficult from a mathematical or computational standpoint; however, these additions would require the input of several adjustable parameters for which little information is known.

A material balance on one component in this stage results in

$$\frac{dN_i}{dt} = Q \frac{P_i}{RT}, \quad [11]$$

where  $N_i$  is the moles of component  $i$  in the stage in liquid form,  $t$  is time,  $Q$  is the gas flow rate,  $P_i$  is the partial pressure of component  $i$ ,  $R$  is the ideal gas constant, and  $T$  is the absolute temperature.

From Raoult's Law, with its implicit assumption of an ideal solution in the liquid phase and an ideal gas,

$$P_i = x_i P_i^{sat}, \quad [12]$$

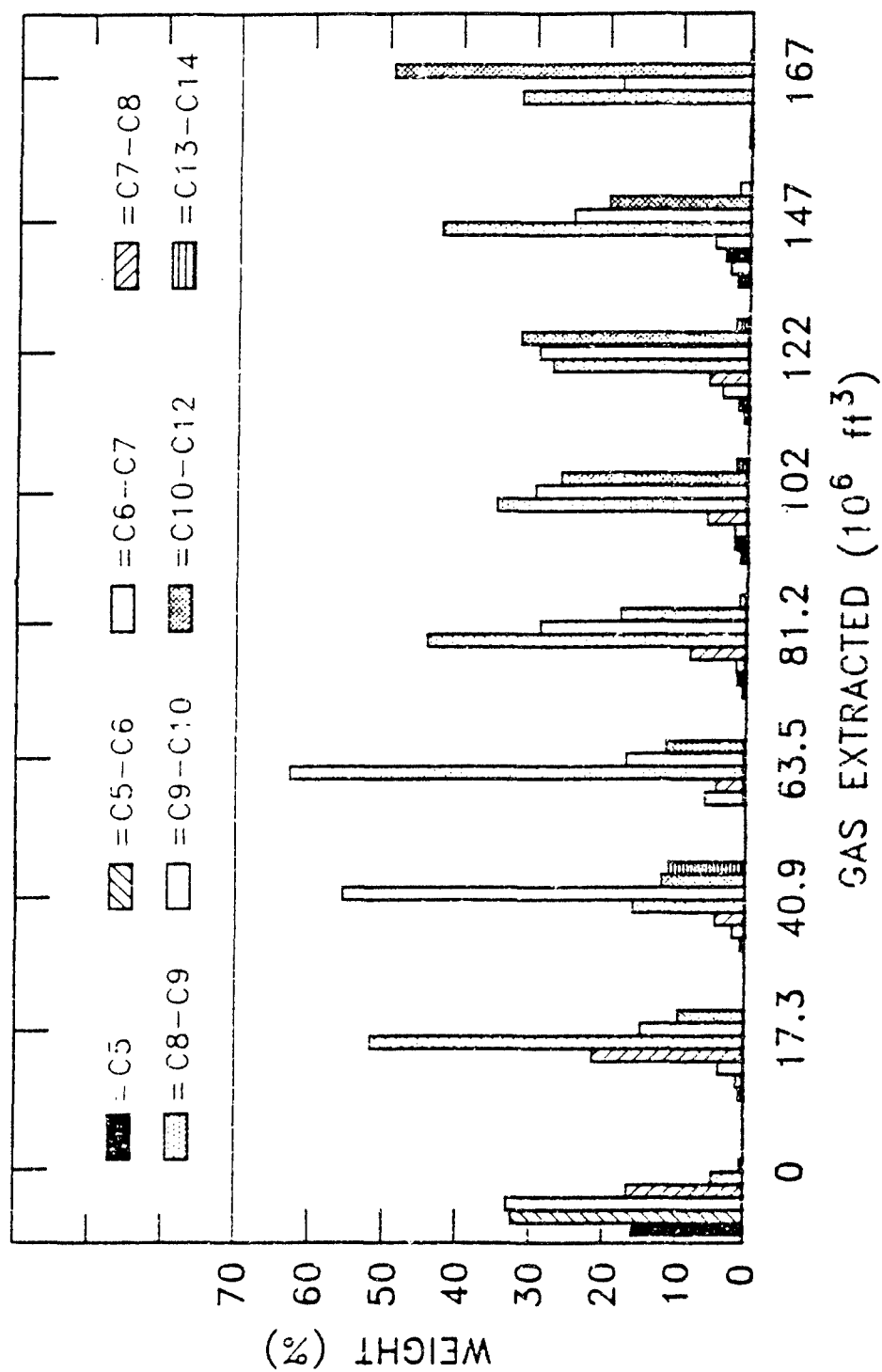


Figure 72. Variation of Hydrocarbon Distribution in Extracted Gas Throughout Demonstration.

where  $P_i^{sat}$  is the vapor pressure of component  $i$  and  $x_i$  is the mole fraction of component  $i$  in the hydrocarbon phase, such that

$$x_i = \frac{N_i}{\sum_{i=1}^n N_i} \quad [13]$$

Combination of the preceding two equations results in

$$\frac{dN_i}{dt} = Q x_i \cdot \frac{P_i^{sat}}{RT} \quad [14]$$

This equation was solved using a simple BASIC program as listed in Volume II. In this program,  $P_i^{sat}$  for each component is calculated using the Antoine equation,

$$\ln(P_i^{sat}) = a - \frac{b}{(T+c)} \quad [15]$$

where  $a$ ,  $b$ , and  $c$  are empirical constants for each compound. Values for these parameters were obtained from Reference 18. Since a typical analysis of JP-4 reports a breakdown of 86 percent paraffins and 14 percent aromatics, the  $P_i^{sat}$  for a hydrocarbon cut was estimated by adding  $0.86 P_i^{sat}$  for the normal paraffin of the range to  $0.14 P_i^{sat}$  of a representative aromatic compound. For instance  $P_6^{sat}$  was estimated as  $0.86 P_{n\text{-hexane}}^{sat} + 0.14 P_{\text{benzene}}^{sat}$ .

Input to the program includes the total initial weight of the hydrocarbons, the weight fraction of each hydrocarbon range, the soil temperature, the venting gas flow rate, the time step size, the total number of time steps and the number of steps between printouts. However, because of the equilibrium assumption, only one run need be made for a given composition and temperature combination. The output may thus be scaled as vapor concentration (grams per liter) and percent of spill remaining as a function of the cumulative gas volume per mass of initial spill. In this manner, the equilibrium removal behavior for any size spill or flow rate may be deduced from one curve.

The weight fractions input to the program were:

C5-C6 - 0	C11-C12 - 0.131
C6-C7 - 0	C12-C13 - 0.105
C7-C8 - 0.166	C13-C14 - 0.053
C8-C9 - 0.223	C14-C15 - 0.029
C9-C10 - 0.16	C15-C16 - 0.016
C10-C11 - 0.116	C16-C17 - 0.001

These weight fractions were derived from analysis of a JP-4 standard.

The concentration results obtained using this model with an input of 26,000 gallons JP-4 initially (27,000-gallon spill minus 1000 gallons collected) are compared with actual readings in Figures 73 (semilog) and 74 (logarithmic). Agreement is particularly good, given the vast simplifications in the model. Some observations may be made in the comparison of the model and field results. First, the initial concentration predicted by the model was a factor of 3 to 4 lower than the actual measured concentration. This indicates that the initial hydrocarbon mixture in the soil contained lighter constituents than in the JP-4 standard used in deviation of the model results. However, agreement is reached in a relatively short period of venting. Poor contacting of airflow with the contaminants would cause the actual results to be initially lower, but with a longer tail than the equilibrium curve. The comparison does not show this to be the main factor in disagreement over the course of the demonstration. However, as venting progresses, the actual results are seen to exhibit a negative departure from the model, indicating either poor contact as zones are cleared of contaminants, providing clear air flow pathways, or indicating a shift toward diffusional control of removal as concluded by Johnson & Sterrett (Reference 20). Biodegradation would cause the actual results to start at the same level as the equilibrium curve, but decrease faster and stay below the equilibrium curve. Although this does not account for all of the disagreement, biodegradation may partially explain the deviation in the latter part of the curve. Although the equilibrium curve was derived for a constant soil temperature of 60°F (15.5°C), the extracted soil gas temperatures increased from 50 to 55°F (10.0 to 12.8°C) in the winter to up to 75°F (23.9°C) in the summer. This would help explain higher actual concentrations and removal rates during middle portions of the venting as temperatures rose, and lower actual concentrations than the model later since the higher earlier removal would leave less volatile contaminants later in venting. A combination of these and possibly other factors is expected to help explain deviations between the measured results and the model; however the agreement is remarkable given the simplicity of the model.

The model was also used to compare the measured vapor phase hydrocarbon distributions with the equilibrium model. Figure 75 shows the variation of the gas composition as indicated by the average number of carbon atoms per molecule calculated by the model superimposed on the results obtained from GC analyses. This averaged carbon number was derived by a summation of the product of the relative weight fraction of each hydrocarbon cut in the gas sample and the number of carbon atoms per molecule for that cut. For example, if the contaminants in a sample were 40 weight percent of C5-C6 hydrocarbons and 60 weight percent C6-C7 hydrocarbons, the average carbon number as defined here would be  $0.4(5) + 0.6(6) = 5.6$ . Agreement between the model and measured results is quite good.

## 6. Discussion

The removal of hydrocarbons by volatilization in the Hill AFB demonstration was representative of soil venting systems, both in terms of mass removal and extracted gas contaminant concentrations. Removal rates and concentrations were very high initially, but they decreased rapidly as venting progressed. This behavior was modelled well in this case by assuming perfect air/contaminant contact and applying the Raoult's Law equilibrium relation.



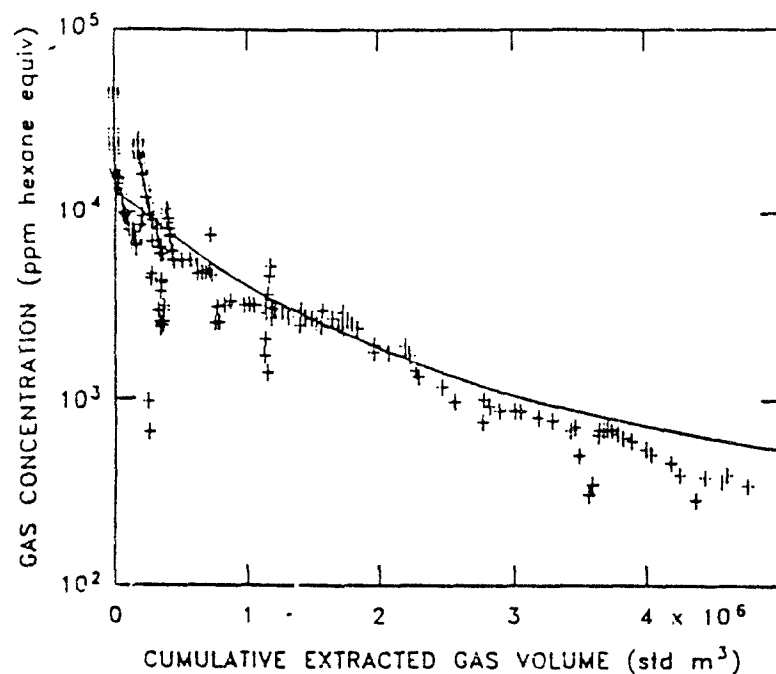


Figure 73. Comparison of Model with Hydrocarbon Concentration Results; Semi-Logarithmic Representation. Model Input - 26,000 Gallons JP-4 at 60°F. (+ = THA measurements; - = model.)

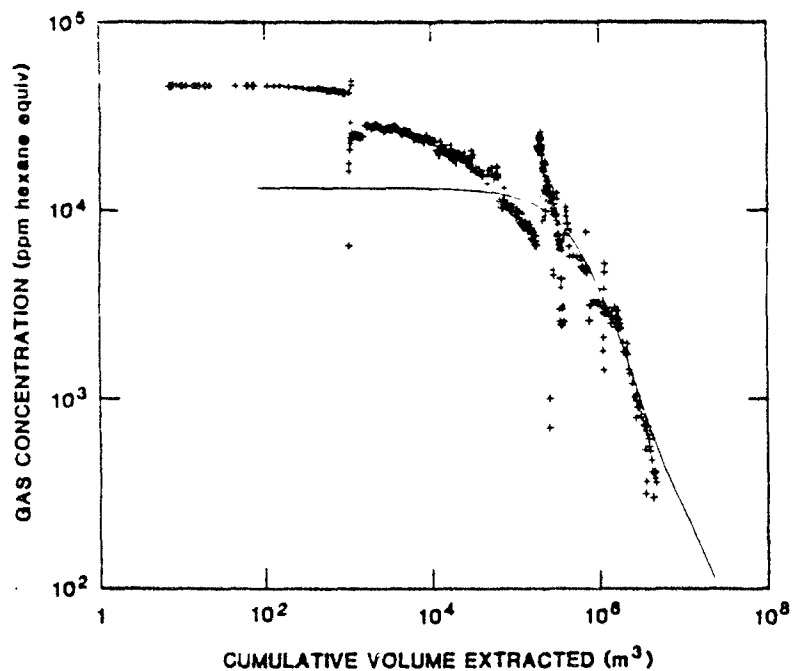


Figure 74. Comparison of Model With Hydrocarbon Concentration Results; Logarithmic Representation. Model Input - 26,000 Gallons JP4 at 60°F. (+ = THA measurements; - = model.)

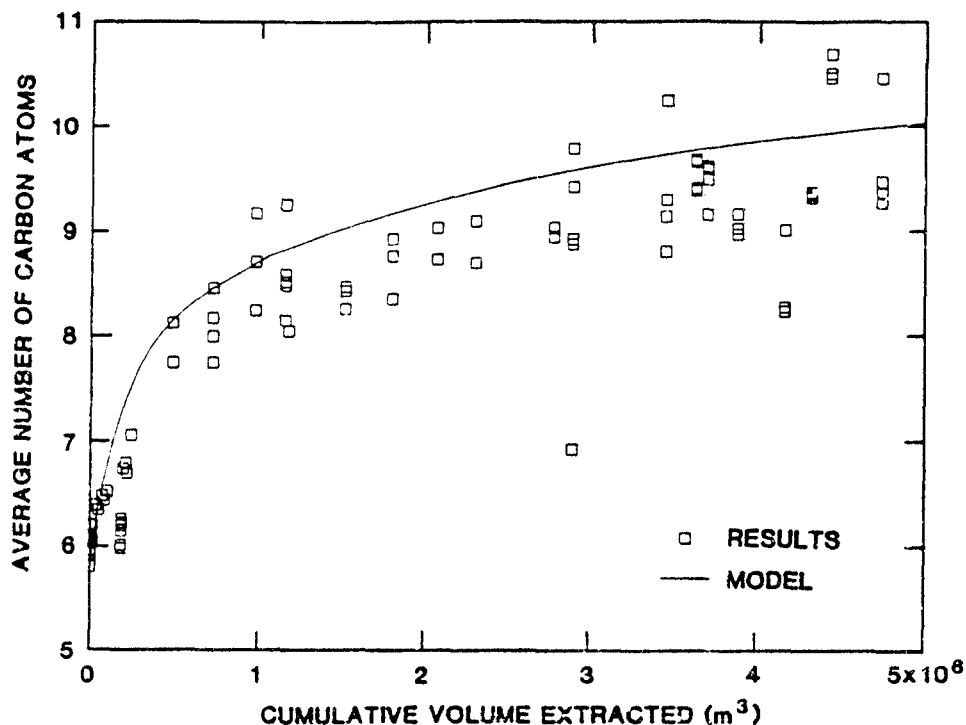


Figure 75. Comparison of Model to Results of Hydrocarbon Composition.

The equilibrium model, therefore, provided a simple but powerful tool for extrapolation of system performance. With this model, it may be seen that removal of JP-4 by volatilization alone will require vast amounts of time beyond the 80-90 percent removal range. For instance, it is predicted that about 325 liters of air per gram of JP-4 initially present is required to achieve 80 percent mass removal by volatilization alone. The value for 90 percent removal is about 800 liters per gram, whereas the value for 95 percent removal is about 1500 liters per gram. Therefore, the time required for removal of the 15 mass percent of the initial spill from 80 to 95 percent removal would be 3.6 times longer than the time necessary for removal of the first 80 percent.

Although venting removes the bulk of the contamination quickly, with such diminishing returns, application of soil venting to JP-4 spills of high soil concentration appears to be somewhat questionable for meeting final cleanup levels in a reasonable amount of time if volatilization were the only factor in removal. Fortunately, the soil aeration induced in the venting process also enhances biological activity, aiding in the removal of the hydrocarbons. Results of investigations into the effects of biodegradation at Hill AFB is included in Section V.E.

## E. BIOACTIVITY

During the course of the soil venting program at Hill AFB, an investigation of *in situ* biodegradation was carried out by Battelle Columbus under a separate contract with the Air Force Engineering and Service Center. This chapter presents the results of these studies. The text is virtually identical to the text of the initial report prepared by Battelle; it has been edited only to produce a consistent format and to eliminate repetition of material already covered in previous sections. Additional observations are added in a separate section following the Battelle text.

### *Enhanced Biodegradation through Soil Venting*

R. E. Hinchee, D. C. Downey, R. R. Dupont, M. Arthur

The objectives of this project were (1) to document biodegradation of JP-4 in the vadose zone at the soil venting installation at Hill AFB, Utah and (2) to conduct laboratory treatability studies to determine the feasibility of engineering increased *in situ* biodegradation of JP-4 in the vadose zone.

#### 1. Background

Fortunately, fuel compounds are biodegradable if natural bacteria are provided an adequate supply of oxygen and basic nutrients. Although natural biodegradation will eventually mineralize most fuel contamination, the process is frequently too slow to prevent the spread of contamination at many sites. Such sites require rapid removal of the contaminant source and groundwater treatment to protect sensitive aquifers. At these sites, an acceleration of the natural biodegradation process is desired.

Over the past two decades the practice of enhanced biodegradation has increased, particularly for treating the soluble fuel components in groundwater (Reference 21). Less emphasis has been given to enhancing biodegradation in the unsaturated zone. A recent field experiment at a jet fuel contaminated site using infiltration galleries and spray irrigation to introduce oxygen, nitrogen, and phosphorous to unsaturated, sandy soils was unsuccessful due to rapid hydrogen peroxide ( $H_2O_2$ ) decomposition and resulting poor oxygen distribution (Reference 22). Soil samples also revealed that little or no hydraulic washing of fuels had occurred even though up to 190 pore volumes of water had passed through the soil (Reference 23). This observation confirms earlier laboratory findings that fuel residuals are occluded in small soil pores, making them inaccessible to passing water (Reference 24). Because of these fundamental limitations, the use of water to uniformly transport nutrients and oxygen through the unsaturated zone has not always proven effective.

As an alternative, a potentially cost-effective method for *in situ* soil remediation is to stimulate soil-indigenous microorganisms to metabolize fuel hydrocarbons in unsaturated soils. Hydrocarbon-utilizing bacteria may constitute less than 0.1 percent of the normal microbial community in unpolluted ecosystems and up to 100 percent in oil-polluted ecosystems (Reference 25). While most surface soils contain microorganisms capable of geologically degrading hydrocarbons *in situ*, the factors that may limit the bioremediation process need to be overcome. These factors include nutrient limitations, toxicity of fuel hydrocarbons and associated contaminants, oxygen limitations, moisture filtration limitations, acidic or basic conditions, and oxygen deficiency. Probably the most important factor in limiting the bioremediation of hydrocarbon-contaminated soils is the lack of oxygen to support microbial metabolism (Reference 26). Insufficient oxygen in fuel-contaminated soils thus plays a role in the persistence of fuels in soils (Reference 25).

Soil venting may be a reasonable means to overcome oxygen limitations and stimulate biodegradation in the vadose zone. The microbial biodegradation of hydrocarbons in soils may be stimulated in the soil venting process, while volatile compounds are simultaneously removed from contaminated soils, or the process may be managed to minimize volatilization.

## 2. Scope/Approach

To address the first objective of this project, documentation of biodegradation in the field, a series of experiments and observations were conducted at Hill AFB. Healy and Daughton (Reference 27) proposed that one of three criteria must be met to document biodegradation: (1) loss of substrate coupled with an increase in microbial biomass, (2) production of metabolites directly from the parent material, and (3) production of indicators of microbial catabolism, such as reduced electron acceptors, or the initiation of physiological responses that are typical of catabolism, such as microbial acclimation. In this study, the emphasis was primarily on the second criterion. Specifically, evolution of  $\text{CO}_2$  and utilization of oxygen were measured *in situ*. In order to address the second objective, the engineering feasibility study, microbial populations and substrate reduction were examined using more homogeneous and controlled laboratory treatability studies.

## 3. Microbial Characterization

Soils were collected at various depths from the uncontaminated background vent location and various locations in the contaminated area. Soil samples from the background vent were collected by Battelle; ORNL supplied the soils from the contaminated area. Immediately after being brought to the surface, representative soil samples from specific depths were placed in sterile polyethylene bottles, sealed, placed on ice, and shipped overnight. The samples were stored at 39°F (4°C) and maintained at field-moist conditions for no more than a few days prior to microbial enumeration.

Microbial characterization of the soils included enumeration of total plateable organisms on nutrient agar (Difco) and on mineral salts agar with JP-4 as the sole carbon source. The enumeration was carried out in triplicate replicates using a tenfold soil dilution method with sterile distilled water as the dilution. Appropriate soil dilutions were pour-plated in the case of nutrient agar and spread-plated in the case of the mineral salts agar plus JP-4. The mineral salts agar contained (per liter): 0.05 grams potassium hypophosphate ( $\text{KH}_2\text{PO}_4$ ), 0.50 grams sodium nitrate ( $\text{NaNO}_3$ ), 0.15 grams magnesium sulfate heptahydrate ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ), 0.05 grams calcium chloride hexahydrate ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ ), 0.05 grams sodium chloride ( $\text{NaCl}$ ), and 0.01 grams ferric chloride hexahydrate ( $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ ). The JP-4 was added to a filter paper that was then taped to the lid of each petri dish; volatile compounds from the filter paper served as the carbon source. After several days of dark incubation at 77°F (25°C), colonies were counted at an appropriate dilution with the aid of a Quebec-lighted colony counter. The results were expressed as the mean plus or minus one standard deviation of colony-forming units per gram soil on a dry weight basis.

The plate counts on the nutrient agar are referred to as "total microorganisms;" those on the JP-4 and mineral salt agar are referred to as "hydrocarbon degraders." The results are illustrated in Figure 76. Significant microbial activity was observed in all the locations; however, at the uncontaminated background vent location, very little microbial activity was observed below 20 feet (6.1 meters). Hydrocarbon degraders appear to be present throughout much of the contaminated site.

## 4. Field Studies

Two different approaches were taken in the field studies: (1) The offgases from the vents were analyzed to attempt to quantify the amount of biodegraded JP-4; and (2) soil gases from the

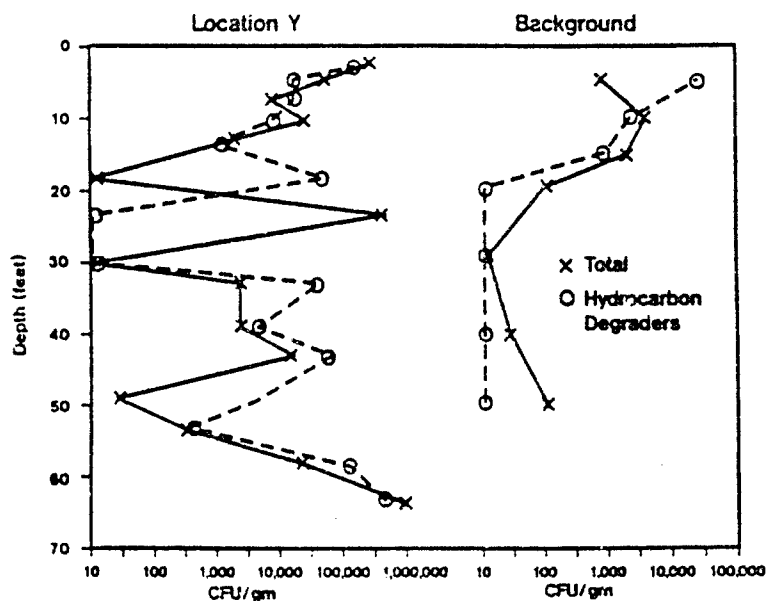
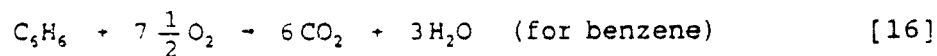


Figure 76. Vertical Distribution of Total and Hydrocarbon Degrading Microorganisms at Hill AFB, Utah, August and October 1988. (Concentrations are the Colony-Forming Units per Gram Dry Weight).

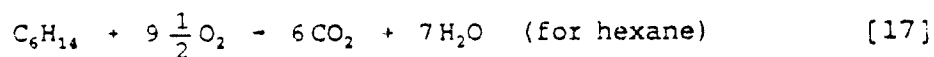
monitoring points during venting shutdown periods were analyzed to estimate specific respiration rates.

#### a. Venting Offgas Studies

Aerobic biodegradation consists of the conversion of a carbon source into biomass and energy. The stoichiometry of aerobic mineralization (that portion of the carbon source utilized for energy) of selected JP-4 constituents may be expressed as:



and



Biodegradation of JP-4 to mineralization may therefore be estimated by determining either oxygen utilization or CO<sub>2</sub> production. The problems associated with this in a soil venting operation such as at Hill AFB include accounting for non-JP-4 carbon respiration and/or inorganic CO<sub>2</sub> sources and sinks. It should be noted that these are only estimates of the JP-4 actually mineralized--those portions converted to biomass or simply partially degraded to another organic compound were not measured. Therefore these estimates of biodegradation must be considered conservative.

### (1) Oxygen and CO<sub>2</sub> Measurement Techniques

Most of the soil gas samples were collected for analysis of oxygen and carbon dioxide content on a real-time basis using Bacharach FYRITE® O<sub>2</sub> and CO<sub>2</sub> monitors. These monitors are routinely used for the determination of O<sub>2</sub> and CO<sub>2</sub> in boiler and furnace flue gases and work on the principle of volume reduction in a closed container following absorption/reaction of a gas with a reaction fluid, similar to the Orsat gas analysis method. These monitors are accurate to  $\pm 0.25$ -0.5 percent over a full scale of 0 to 21 percent by volume for both O<sub>2</sub> and CO<sub>2</sub>. They do require, however, that readings be taken at temperatures near 68 to 77°F (20 to 25°C) to maintain both their accuracy and precision. When ambient temperatures were in this operating range, O<sub>2</sub> and CO<sub>2</sub> measurements were made at each location; while determinations during periods with much lower temperatures required the analysis of grab samples of vent contents in a heated sampling trailer located on site.

Approximately two vent volumes were purged from each vent before sample collection. Purging was carried out using personal monitoring pumps, operated at 2 to 4 liters per minute, which were connected to each well by Teflon® tubing and stainless steel tubing fittings. For those samples analyzed directly at the well, the personal vacuum pump was disconnected after the well was purged, and a small hand vacuum pump was attached to the well head. The hand pump was evacuated by squeezing the pump bulb five times before it was attached to a FYRITE® reaction chamber. The well gas was introduced into the reaction chamber by squeezing the pump bulb an additional 18 times while compressing the chamber inlet valve. The reaction chamber was inverted two times to allow the gas and chamber solution to react, then the solution in the calibrated sight chamber was allowed to equilibrate for approximately 15 seconds before a reading was taken. Readings were taken as percent volume of O<sub>2</sub> or CO<sub>2</sub> and were generally read to the nearest 0.5 percent. For those samples collected at ambient temperatures below 68 to 77°F (20 to 25°C), a Tedlar® bag was connected to the effluent port of the personal monitoring pumps following well purging to collect approximately 2 liters of vent gas. These Tedlar® bags were then allowed to reach optimum analysis temperature in the heated sampling trailer (about 10 minutes) before being analyzed as described above.

For quality assurance/quality control purposes, the FYRITE® monitors were calibrated to ambient air at each well field sampling event. In addition, FYRITE® results were routinely compared with those of a Universal Enterprises Model C5 portable oxygen analyzer, and Gastech direct reading CO<sub>2</sub> tubes to verify their accuracy from independent vent well measurements. A limited number of CO<sub>2</sub> analysis were also performed utilizing a gas chromatograph with a thermal conductivity detector.

## (2) Background Vent

The background vent was installed in an uncontaminated location geologically similar to the main venting site. The vent was operated at an average flow rate of 55 feet<sup>3</sup>/minute (0.026 m<sup>3</sup>/second). At several times throughout the study, gas samples were collected from the background vent for O<sub>2</sub> and CO<sub>2</sub> analysis. In general, oxygen levels were at or only slightly below atmospheric. Carbon dioxide was typically higher than atmospheric, but well below 1 percent. The average level appeared to be approximately 0.2 percent, generally about 10 times higher than atmospheric.

## (3) Carbon Isotope Studies

In order to further investigate the source of carbon dioxide in the soil gases, the isotopic ratios of <sup>13</sup>C/<sup>12</sup>C were determined.

Four different gas samples were collected for analysis: one from the background vent; one from monitoring point M, a contamination location which had high CO<sub>2</sub> levels; one from Vent 10 during active venting; and one atmospheric sample. The samples were passed through activated carbon filters to remove any hydrocarbon vapor and collected in Tedlar<sup>®</sup> bags for transportation to the laboratory.

The carbon dioxide in the gaseous samples was isolated from other components by a series of freeze-thaw steps. First, the sample was passed through a dry ice alcohol trap that removed moisture and other condensable gases. The residual gases were then passed through a liquid nitrogen trap, freezing the carbon dioxide. The system was evacuated to remove any noncondensable fractions. The frozen gas was thawed and the above steps repeated at least two times until there was no noncondensable fraction.

The pure sample of carbon dioxide gas was analyzed on a dual-inlet, Nier-type mass spectrometer. Carbon dioxide evolved from the reaction of phosphoric acid with a Belemnite americana from the Cretaceous, Peedee Formation, South Carolina, is used as a reference gas. The isotopic ratios of an unknown are reported as a per-mil deviation from the standard using the 'δ' notation:

$$\delta = \frac{1000 (R_{sample} - R_{std})}{R_{std}} \quad [18]$$

where  $R_{sample}$  and  $R_{std}$  is the ratio of <sup>13</sup>C to <sup>12</sup>C in the sample or the standard, respectively.

The ratio of the two stable isotopes of carbon, <sup>13</sup>C and <sup>12</sup>C, is characteristic of the source of carbon in a given sample of gas, liquid, or solid. Typical ranges of δ values for different source materials are shown in Figure 77. As seen in this figure, the δ values for organic material and the organism are lower, that is enriched in the lighter isotope, compared with the atmospheric carbon dioxide.

Isotopic composition of gases produced by the oxidation of the organic material, either as a result of plant respiration or by the degradation of petroleum and other hydrocarbons, also is lower than that of atmospheric  $\text{CO}_2$ . Thus,  $\delta$  values of surface gas samples may be used to identify the subsurface source of carbon.

The isotopic values of four gas samples taken from the Hill AFB site are shown in Table 15 and illustrated in Figure 77. Isotopic compositions of the atmospheric sample (-11.7 per mil) and the sample from the background vent (-23.6 per mil) are similar to those reported for the atmospheric  $\text{CO}_2$  and plant respiratory  $\text{CO}_2$ , respectively. The background vent defines the background isotopic composition for uncontaminated soil gas in the area.

Vent 10 and monitoring point M are in the contaminated region, and isotopic values of gases from these two vents (-27.3 and -29.4 per mil) are lower than the background vent. Monitoring point M is a static monitoring point in the contaminated region and will have the greatest component of  $\text{CO}_2$  produced by the degradation of hydrocarbons. Vent 10 is an active vent and would be expected to have some contribution of the isotopically heavier, plant respiratory  $\text{CO}_2$  and atmospheric  $\text{CO}_2$ . This supports the  $\text{O}_2$  and  $\text{CO}_2$  analysis observations in which the background vent exhibited  $\text{CO}_2$  concentrations elevated above atmosphere but below 1 percent. It appears that the soil gas extracted by the venting operation contained something on the order of 0.2 percent  $\text{CO}_2$  as the result of non-JP-4 respiration.

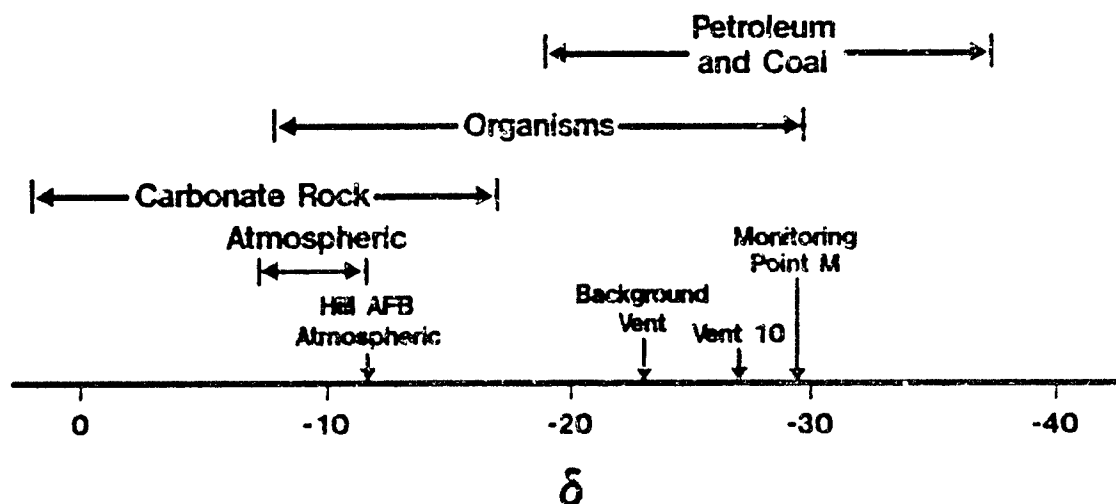


Figure 77. Isotopic Content of Off-Gases Collected from Hill AFB, Utah, and Various Other Environmental Forms of Carbon. (Environmental carbon isotopic content based on Reference 29. Refer to text for identification of isotopic standard.)



TABLE 15. RESULTS OF ISOTOPIC ANALYSIS OF GASES COLLECTED IN JUNE 1989 FROM THE HILL AIR FORCE BASE, UTAH, VENTING SITE

SAMPLE	CO <sub>2</sub> (Percent)	$\delta^{13}\text{C}$
Atmospheric	0.03	-11.7
Background Vent	0.2	-23.6
Monitoring Point M	9.5	-29.4
Vent 10	0.6	-27.3

#### (4) Biodegradation Estimates

Between 18 December 1988 and 1 April 1989, a total of 8,642,000 ft<sup>3</sup> (245,000 m<sup>3</sup>) of soil gas was extracted from the Hill AFB site. The concentration of CO<sub>2</sub> and O<sub>2</sub> varied considerably during this time, as indicated in Figure 78. The depletion of O<sub>2</sub> and enrichment of CO<sub>2</sub> in the vent gas, as compared to the background vent, suggests aerobic degradation of JP-4 hydrocarbon. The large drop in O<sub>2</sub> and rise in CO<sub>2</sub> concentration at approximately 50 days (400,000 scf extracted) was related to restarting the vent system following a nine day shut-down period.

To carry out a mass balance at the site, all vent gas constituents were converted to an equivalent C basis. JP-4 fuel-C was determined based on direct readings of the total hydrocarbon analyzer calibrated to hexane, corrected by the ratio of C to hexane, i.e.:

$$\text{JP-4 Fuel Carbon} = \text{Fuel-Hexane} (72 \text{ g C}/86 \text{ g hexane}) = \text{Fuel-Hexane} (0.837) \quad [19]$$

Calculations for CO<sub>2</sub> were similar, with CO<sub>2</sub>-C calculated by the product of CO<sub>2</sub> concentration and the fraction of C in CO<sub>2</sub>, i.e., 12 g C/44 g CO<sub>2</sub>. Oxygen equivalent C was determined based on the oxygen deficit (below background O<sub>2</sub> levels) measured in the vent gas over time, the oxygen equivalent of hexane (3.5 g O<sub>2</sub>/g hexane), and the C/hexane ratio shown in the equation above. It should be noted that estimates of biodegradation based on CO<sub>2</sub>/O<sub>2</sub> data are conservative as neither consider JP-4 converted to biomass or partially degraded.

Based upon these calculations (included in Appendix J, unpublished - available from ORNL and AFESC), the mass of JP-4 as carbon removed or degraded between 18 December and 1 April 1989 may be estimated as: 25,264 pounds (11,500 kg) volatilized and 4,850 or 4,698 pounds (2200 or 2130 kg) biodegraded (calculated from O<sub>2</sub> deficit and CO<sub>2</sub> increase respectively). These two

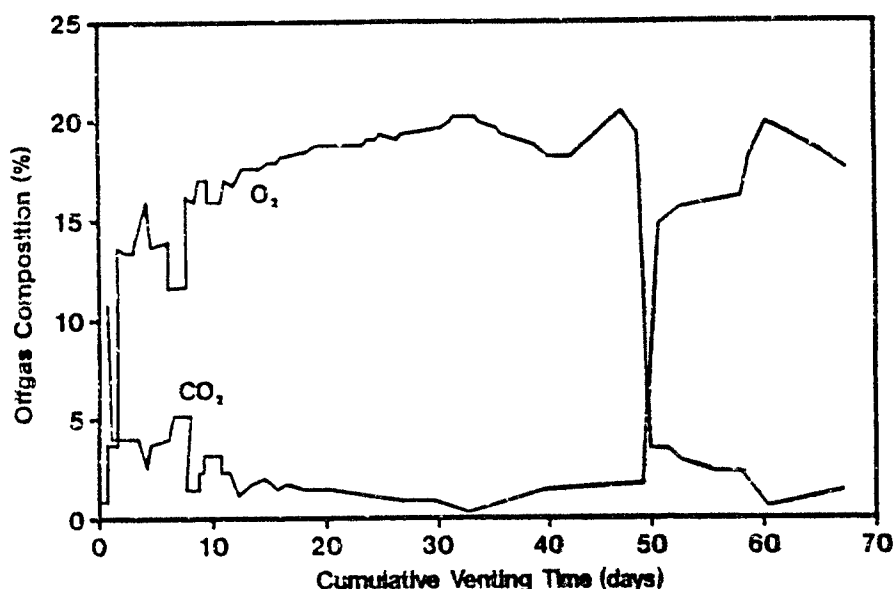


Figure 78. Variation of Oxygen and Carbon Dioxide Concentrations in Extracted Gas With Time for the Period 18 December to 1 April 1989.

results agree remarkably well. Figure 79 illustrates the relative role of biodegradation compared to volatilization over time at the site. Over the 70-day period of actual operation (not calendar days), apparent biodegradation relative to volatilization was initially 30 to 40 percent and then dropped off to 15 to 20 percent on a cumulative basis. This decline may only be an artifact of increasing venting rates, which would increase volatilization rates but have little effect on biodegradation. The rapid decline was also partly due to the initial purge of CO<sub>2</sub> which had accumulated in soil gas. It is also possible that this decline could be due to drying of the soils over this period; however, *in situ* soil moisture measurements showed little change in moisture content below 10 feet (3.0 meters).

#### b. *In situ* Respiration Studies

Although CO<sub>2</sub> and O<sub>2</sub> in the venting offgas provide a good indication of total site respiration, it is difficult to determine either the specific respiration rates or spatial variability in respiration rates. In order to do this, the monitoring points were monitored for O<sub>2</sub> and CO<sub>2</sub> during periods of venting shutdown. This allowed for determination of site-specific O<sub>2</sub> utilization and CO<sub>2</sub> production rates. Three different *in situ* respiration tests were conducted as follows: the first beginning on 19 December 1988, after the first day of venting, during which time 45,000 ft<sup>3</sup> (13,000 m<sup>3</sup>) of air were removed from vent well 7; the second beginning on 13 January 1989 after the first 3 weeks of venting, prior to which time 540,000 ft<sup>3</sup> (15,300 m<sup>3</sup>) of air were removed; and the third beginning on 26 May 1989 after 6 months of venting, during which time 45,000,000 ft<sup>3</sup> (1.27 x 10<sup>6</sup> m<sup>3</sup>)

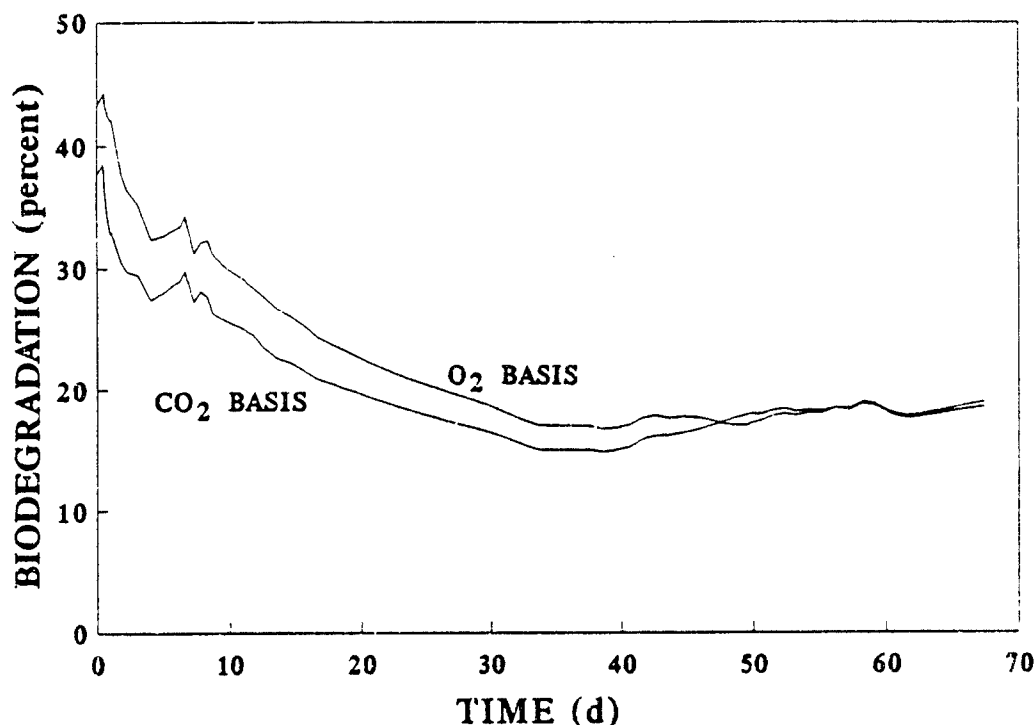


Figure 79. Contribution of Biodegradation to JP-4 Remediation at the Hill AFB, Utah, Venting Site, 18 December 1988 to 1 April 1989.

were removed. Assuming contaminated site dimensions of 200 feet x 100 feet x 40 feet (61 meters x 30.5 meters x 12.2 meters) and an air-filled porosity of 0.30, this would represent an air volume in the contaminated site of approximately 240,000 ft<sup>3</sup> (6800 m<sup>3</sup>). Based on this calculation, the pore volumes of air extracted prior to the *in situ* respiration tests would be 0.18, 2.3 and 190.

Prior to initiating soil gas venting, O<sub>2</sub> and CO<sub>2</sub> concentrations were measured on 7 December 1988. These results are illustrated in Figure 80. The soil gas oxygen concentrations at the beginning and end of each of the *in situ* respiration tests are illustrated in Figures 81-86. Figure 87 illustrates the results of one of these tests at monitoring point Y, and the results of the successive tests at monitoring points Y and M are illustrated in Figures 88 and 89.

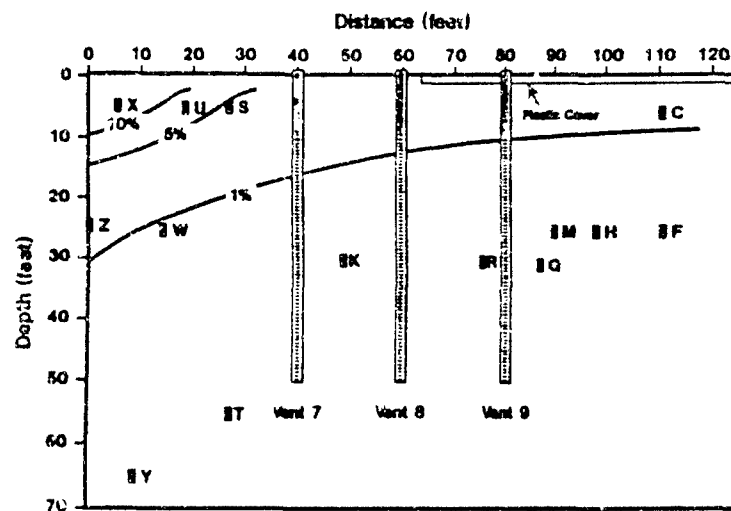


Figure 80. Oxygen Concentrations in Soil Gas on 7 Dec 1988 Prior to Any Venting.

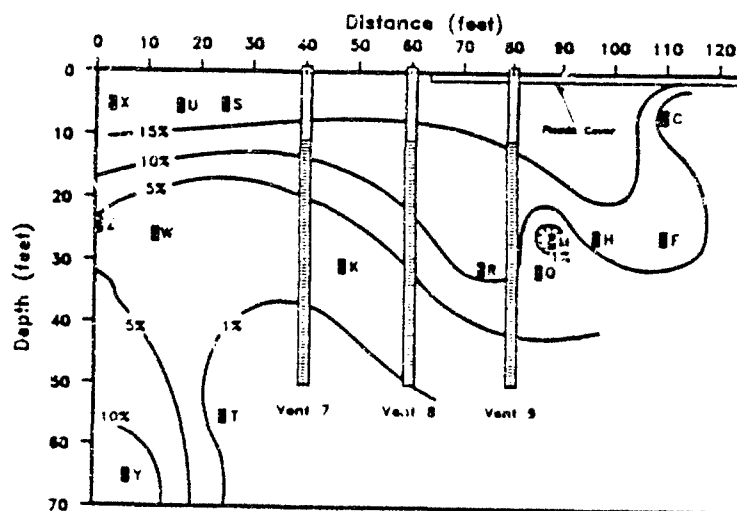


Figure 81. Oxygen Concentrations in Soil Gas on 19 December 1988 at the Initiation of the First *In Situ* Respiration Test.

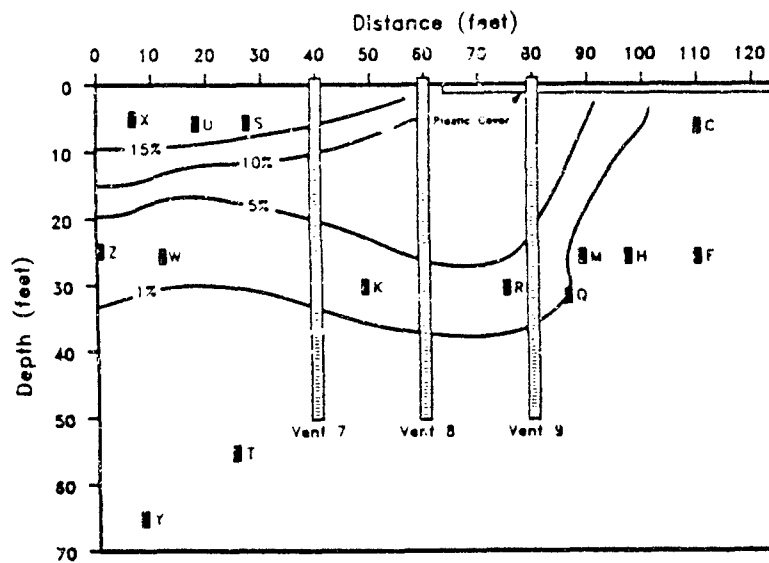


Figure 82. Oxygen Concentrations in Soil Gas on 22 December 1988 at the Conclusion of the First *In Situ* Respiration Test.

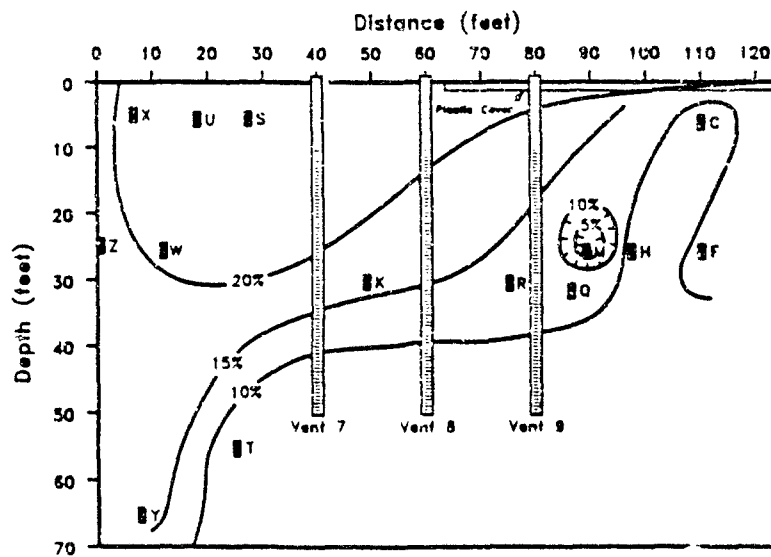


Figure 83. Oxygen Concentrations in Soil Gas on 13 January 1989 at the Initiation of the Second *In Situ* Respiration Test.

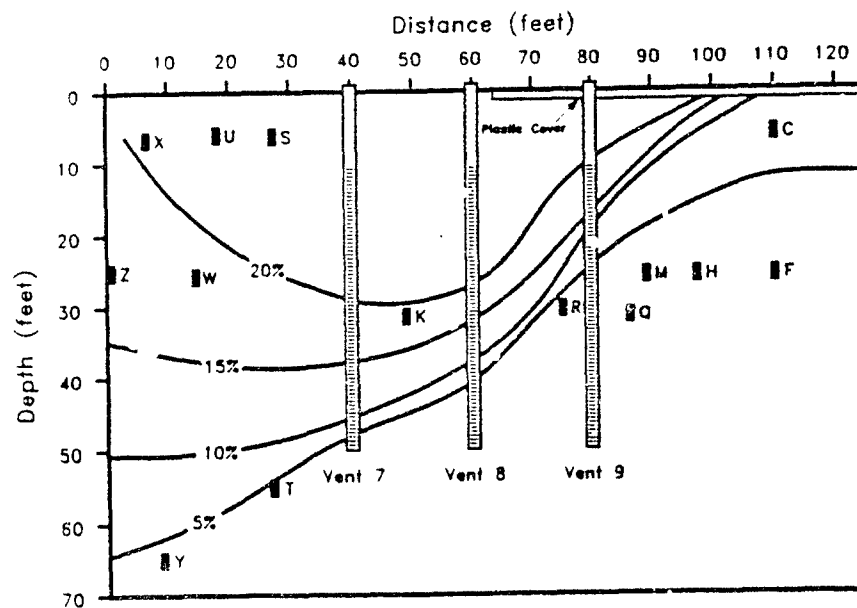


Figure 84. Oxygen Concentrations in Soil Gas on 18 January 1989 at the Completion of the Second *In Situ* Respiration Test.

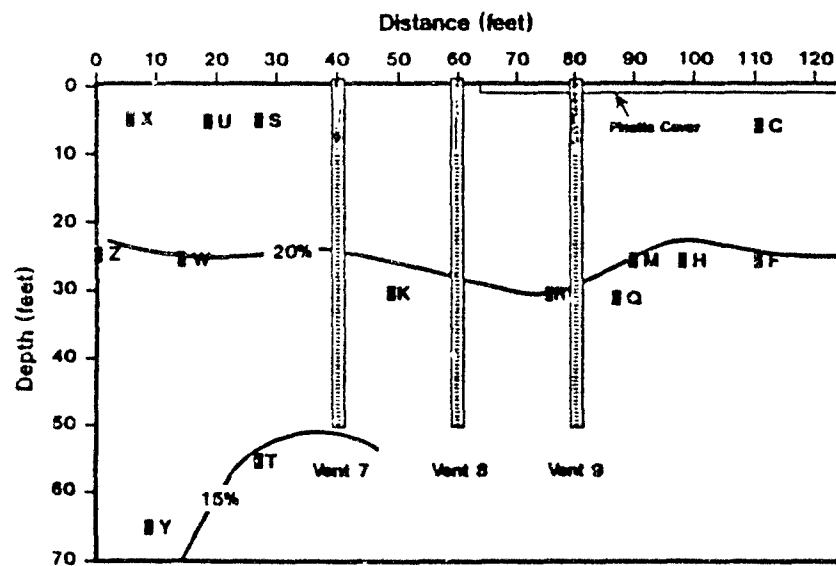


Figure 85. Oxygen Concentrations in Soil Gas on 26 May 1989 at the Initiation of the Third *In Situ* Respiration Test.

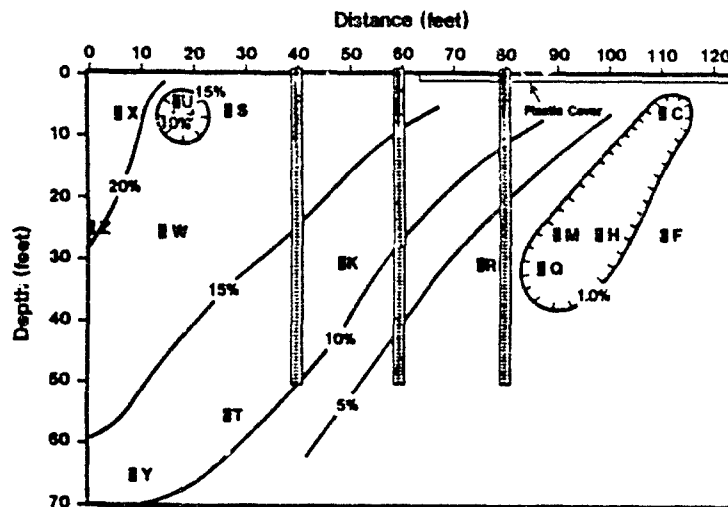


Figure 86. Oxygen Concentrations in Soil Gas on 9 June 1989 at the Conclusion of the Third *In Situ* Respiration Test.

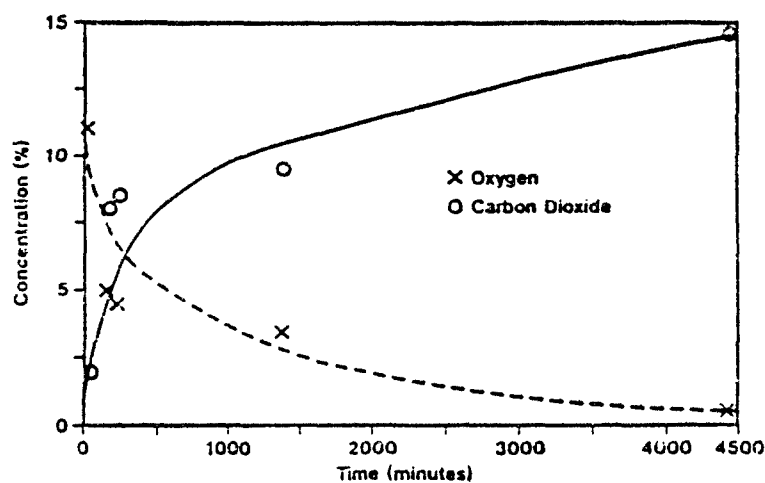


Figure 87. The Results of the first *In Situ* Respiration Test at Monitoring Point Y (65 Feet Below Land Surface), 19 December 1989.

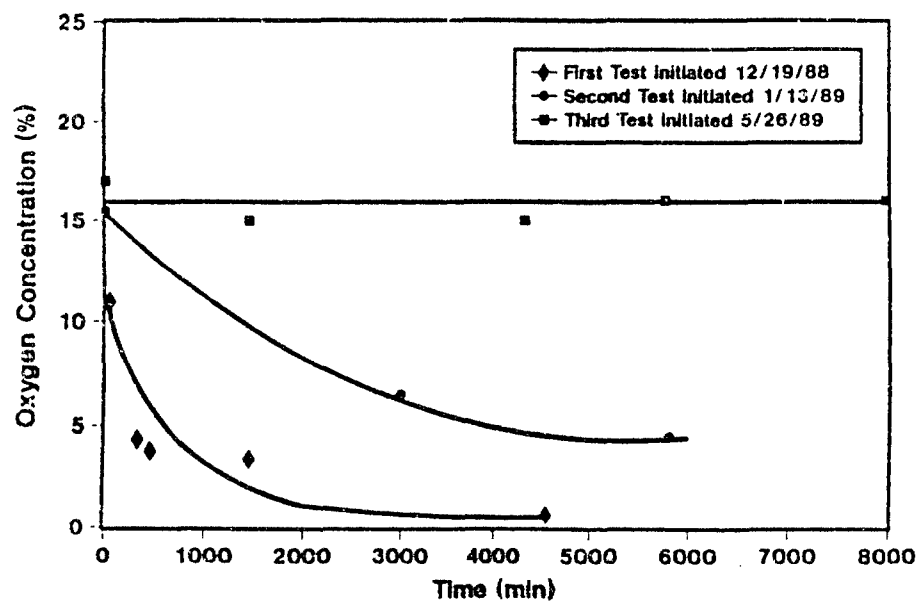


Figure 88. The Results of the Three Successive *In Situ* Respiration Tests at Monitoring Point Y (65 Feet Below Land Surface).

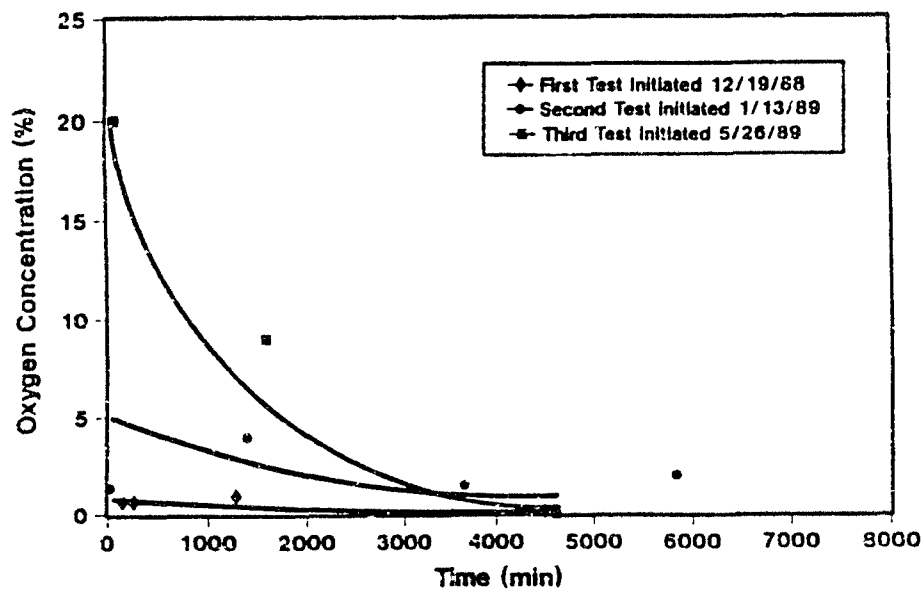


Figure 89. The Results of the Three Successive *In Situ* Respiration Tests at Monitoring Point M (25 Feet Below Land Surface).



At the completion of the third *in situ* respiration test, gas from the monitoring points and some of the vent wells were field screened for hydrocarbon vapor as well as CO<sub>2</sub> and O<sub>2</sub>. This was done using a portable TIP, with a photo-ionization detector. Concentrations are reported as parts-per-million hydrocarbons. The results of these tests are illustrated in Figures 90 and 91. Many of the monitoring points had greater than 1500 ppm of hydrocarbons, and these points generally had low O<sub>2</sub> and relatively high CO<sub>2</sub>. This trend is more apparent in the vent data (Figure 91). The vents screened across a 40-foot (12.2-meter) interval intersect numerous contaminated and uncontaminated zones. The gases are therefore a blend of the various zones. The higher hydrocarbon concentrations are diluted by less contaminated zones. As a result, all hydrocarbon concentrations are within the detectable range and indicate a good correlation between hydrocarbon and CO<sub>2</sub> content and an inverse relationship between hydrocarbon and O<sub>2</sub> content.

Oxygen utilization rates determined in the *in situ* respiration tests are summarized in Table 16. The first order oxygen utilization rates measured *in situ* varied from 0.029 to 10.9 x 10<sup>-4</sup> minute<sup>-1</sup>. At some monitoring points at times no detectable oxygen uptake was measurable. Monitoring points Y (Figure 88) and M (Figure 89) illustrate this point. At the time of the first shutdown test, Y had a fairly high respiration rate; however, after 6 months of venting there was no detectable respiration.

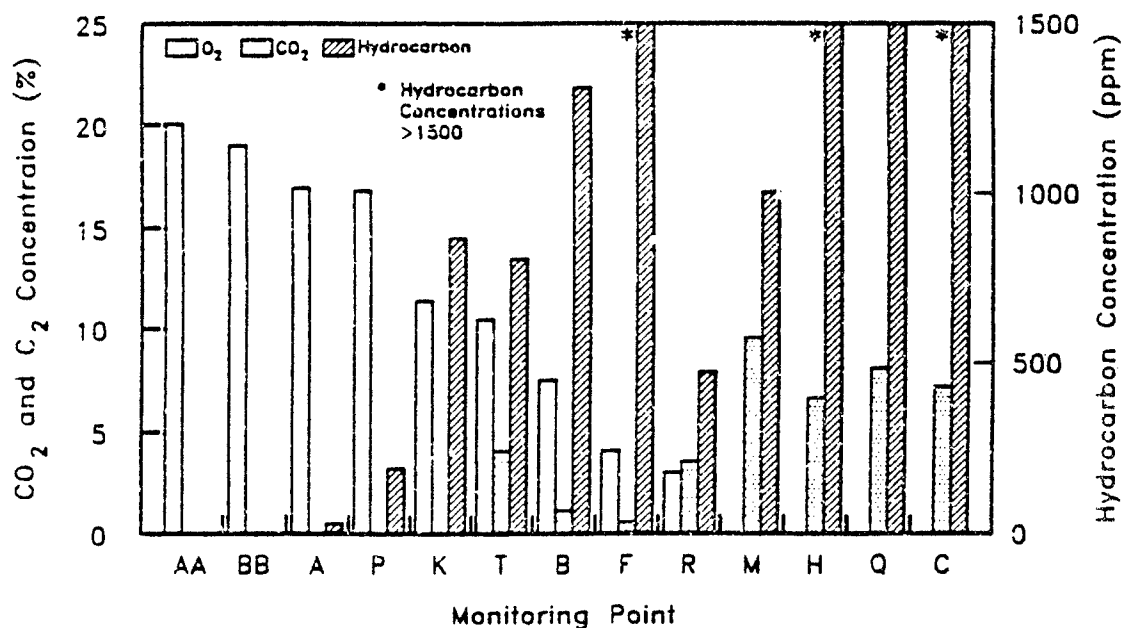


Figure 90. JP-4 Hydrocarbon (HC), O<sub>2</sub> and CO<sub>2</sub> Concentrations 9 June 1989 in the Monitoring Points at the Conclusion of the Third *In Situ* Respiration Test.

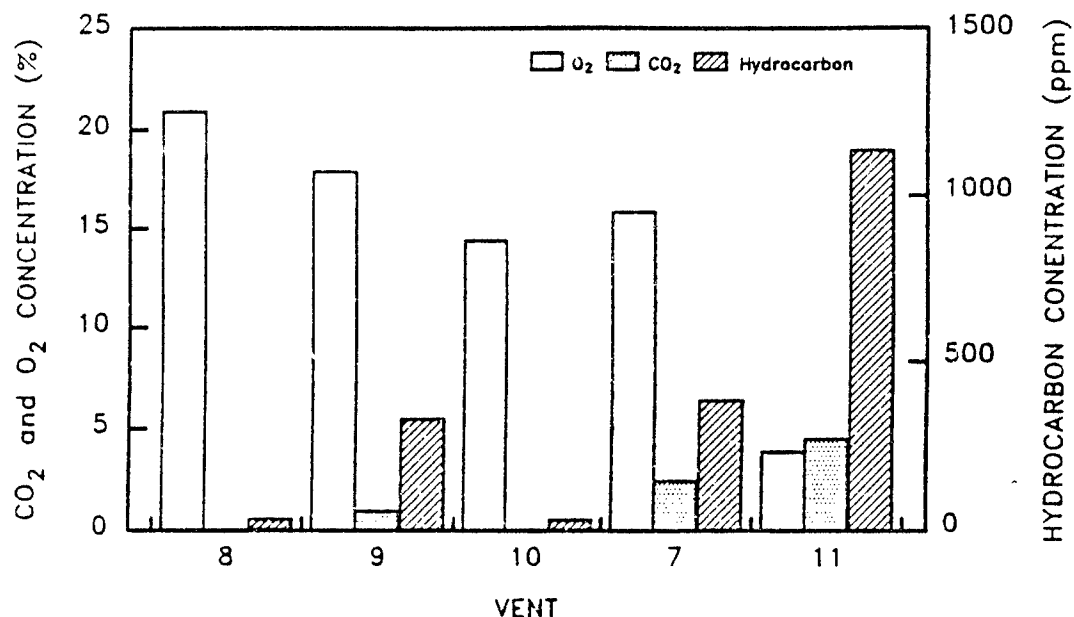


Figure 91. JP-4 Hydrocarbon (HC), O<sub>2</sub> and CO<sub>2</sub> Concentrations 9 June 1989, in the Vents at Conclusion of the Third *In Situ* Respiration Test.

Conversely at monitoring point M, at the time of the first and second *in situ* respiration tests, the oxygen levels were so low that no respiration could be detected. At the third test, however, the location became oxygenated and a relatively high rate of respiration was measured. It is reasonable to conclude that the changes at monitoring point Y were a result of the location becoming clean. Soil gas hydrocarbon measurements with a field portable TIP of only 77 ppm support this conclusion. At location M, it is likely that the microbial community was active from the beginning, but initially oxygen limited. The presence of oxygen at M after 6 months may actually indicate reduced respiration and reduced oxygen demand.

Based upon the data collected, it is difficult to interpret the short-term trends and variability observed; however, it is apparent that significant respiration was occurring in the JP-4 contaminated vadose zone. Based upon the background vent studies, no such respiration was occurring under similar conditions in an uncontaminated location.

##### 5. Bench-Scale Studies

The objective of this study was to determine the feasibility of engineering an increase in the biodegradation observed in the field studies. This was done by augmenting a composite Hill AFB soil with nutrients and moisture.

TABLE 16. RESULTS OF *in situ* RESPIRATION TESTS WITH  $R^2 > 0.60$  CONDUCTED AT HILL AIR FORCE BASE, UTAH. (THE RATE CONSTANTS ARE THE FIRST-ORDER OXYGEN UTILIZATION CONSTANTS  $\times 10^{-4} \text{ MIN}^{-1}$ .)

MONITORING POINT	DEPTH (feet)	DEPTH (meters)	<i>In Situ</i> RESPIRATION TEST					
			December 1988		January 1989		May-June 1989	
			K	$R^2$	K	$R^2$	K	$R^2$
A	30.0	9.1	--	--	--	--	0.061	0.63
B	30.0	9.1	--	--	1.2	0.95	0.39	0.83
C	6.0	1.8	--	--	--	--	4.8	0.87
F	25.0	7.6	--	--	--	--	0.68	0.79
H	25.0	7.6	--	--	--	--	2.1	0.89
K	30.0	9.1	--	--	3.8	0.75	--	--
M	25.0	7.6	--	--	--	--	7.7	0.86
N	45.0	13.7	--	--	0.37	0.70	--	--
P	30.0	9.1	10.	0.77	0.93	0.77	--	--
Q	30.0	9.1	3.7	0.99	--	--	2.3	0.99
R	30.0	9.1	--	--	--	--	0.85	0.88
S	6.0	1.8	--	--	--	--	0.091	0.91
T	55.0	16.8	--	--	0.42	0.95	0.17	0.67
U	6.0	1.8	--	--	--	--	0.36	0.77
W	55.0	7.6	--	--	0.32	0.99	0.036	0.78
X	6.0	1.8	--	--	--	--	0.029	0.71
Y	65.0	19.8	5.9	0.93	2.1	0.95	--	--
AA	30.0	9.1	--	--	0.27	0.99	--	--

#### a. Experimental Design

Fifteen soil columns were set up in the laboratory; 12 were treatment columns and 3 were killed controls [chemically treated with 500 mg/kg cadmium chloride ( $\text{CdCl}_2$ ) and 500 mg/kg mercuric chloride ( $\text{HgCl}_2$ ) to avoid autoclaving]. The columns were 12 inches (30.5 cm) deep and 1.5 inches

(3.8 cm) wide. Each column contained 0.113 pounds (250 grams) of soil on a dry-weight basis. The soil in the columns was composited from several JP-4 contaminated soil samples collected by ORNL at Hill AFB. The concentration of fuel in the composited soil was adjusted to approximately 1000 mg/kg by dosing with JP-4. The experimental design included three soil moisture levels: 25, 50, or 75 percent of field capacity, (6.1, 12.2, and 18.3 percent moisture) in duplicate; the triplicate sterile controls were nutrient treated and held at 50 percent of field capacity. This compares with native soil moistures, as measured at the background vent of 1.4 to 18.0 percent. Of the seven soil samples analyzed, however, five had moisture levels below the 25 percent of field capacity. Duplicate columns at each moisture level were amended with 2 percent (w/w) Restore® 375. Restore® 375 is an FMC commercial nutrient formulation for *in situ* biodegradation in groundwater. Its composition is 50 percent ammonium chloride ( $\text{NH}_4\text{Cl}$ ), 20 percent sodium phosphate ( $\text{Na}_3\text{PO}_4$ ), 17.5 percent sodium tripolyphosphate ( $\text{Na}_5\text{P}_3\text{O}_{13}$ ), and 12.5 percent monosodium phosphate ( $\text{NaH}_2\text{PO}_4$ ). Three method blank columns (no soil) were included in the experimental design. The temperature was monitored at 77.9°F (25.5°C). At least weekly, the soil columns were weighed to determine moisture losses; distilled water was added as necessary to maintain the columns at their initial moisture content.

Each soil column was sealed on either end with a rubber stopper that contained a glass tube. The glass tube entering the bottom of each column was fitted with a fitted glass diffuser and was attached by rubber tubing to the air inlet. The glass tube exiting the top of each column was connected by rubber tubing to individual alkali traps to capture evolved  $\text{CO}_2$ . The columns were constantly vertical in an upflow manner. All columns were vented with humidified air that passed through alkali scrubbers to remove background  $\text{CO}_2$ . The offgases from each column were passed through individual traps of 1N sodium hydroxide ( $\text{NaOH}$ ).

Periodically (at least weekly) over a 48-day test period the alkali traps for each soil column were replaced with fresh alkali. The  $\text{CO}_2$  trapped in the used alkali was precipitated as barium carbonate ( $\text{BaCO}_3$ ) by the addition of saturated barium chloride ( $\text{BaCl}_2$ ). The amount of  $\text{CO}_2$  trapped was then determined by titration with hydrochloric acid ( $\text{HCl}$ ) using an autotitrator. The cumulative evolution of  $\text{CO}_2\text{-C}$  over 48 days was calculated as follows:

$$\text{CO}_2\text{-C} = \sum [(B - V)NE] \quad [19]$$

where  $V$  = mL of acid for end-point titration of the alkali in the  $\text{CO}_2$  traps from individual treatment or sterile soil columns,

$B$  = average mL of acid for end-point titration of the alkali in the  $\text{CO}_2$  traps from the duplicate method blank columns,

$N$  = Normality of acid used for the titrations, and

$E$  = the equivalent weight of  $\text{CO}_2\text{-C}$ , i.e., 6 mg/meq.

Soils were analyzed for hydrocarbon content at the beginning and end of the incubation period. To perform the hydrocarbon analysis, 30 grams of each soil were extracted with 100 mL of acetone by shaking for 30 minutes. Thirty mL of the extract were then diluted with distilled water to a volume of 200 mL, which was poured through a Pre-Sep C-18 column. The hydrocarbons

retained on the Pre-Sep column were eluted with 1 mL of dichloromethane. One microliter of the eluate was then injected into a Hewlett-Packard 5890 gas chromatograph (GC) equipped with a flame-ionization detector. The other GC conditions were as follows:

Column: 6 feet x 2 mm ID, 3 percent OV 101  
 Injector: 9°C  
 Detector: 300°C  
 Temperature Program: 40°C for 4 minutes, increasing to 260°C for 4 minutes  
 (total run time = 30 minutes).

The results are expressed as milligrams of JP-4 per dry kilogram of soil compared to a JP-4 standard. Microbial enumerations for total and hydrocarbon degenerating microorganisms were also conducted before and after the test period.

#### b. Results

The cumulative evolution of CO<sub>2</sub> through 48 days for all columns is shown in Figure 92. Those columns receiving nutrients showed the greatest evolution of CO<sub>2</sub>-C. Figure 93 illustrates the results of the bench control. This control received the Restore•375 treatment and was at 50 percent

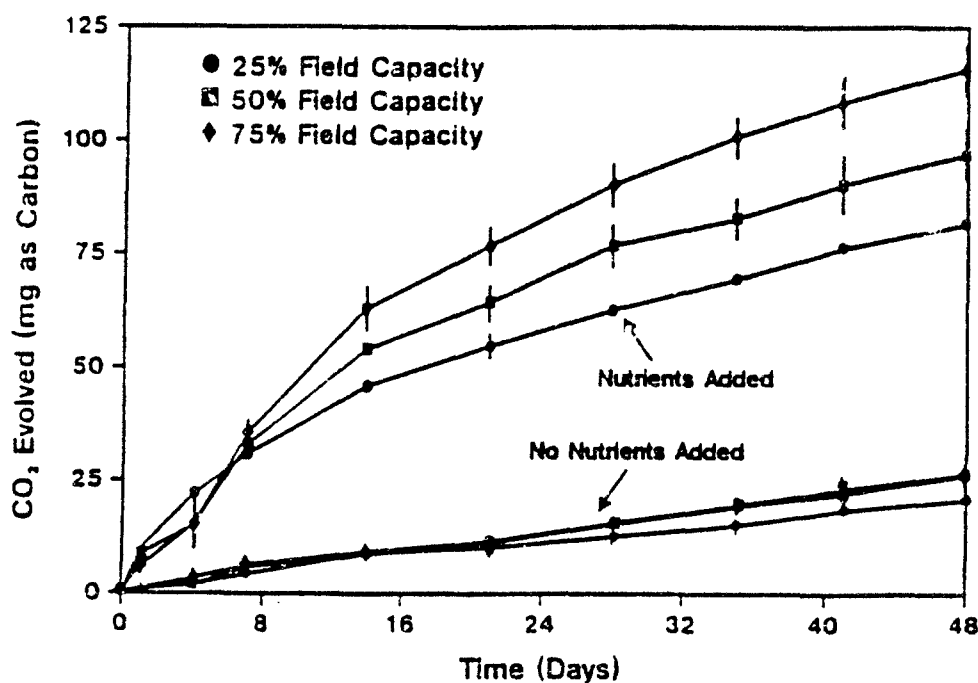


Figure 92. Results of Bench Scale Treatability Studies with Hill AFB, Utah, Soils. (The points are the means of two tests with the ends of the bars representing the results of each separate test.)

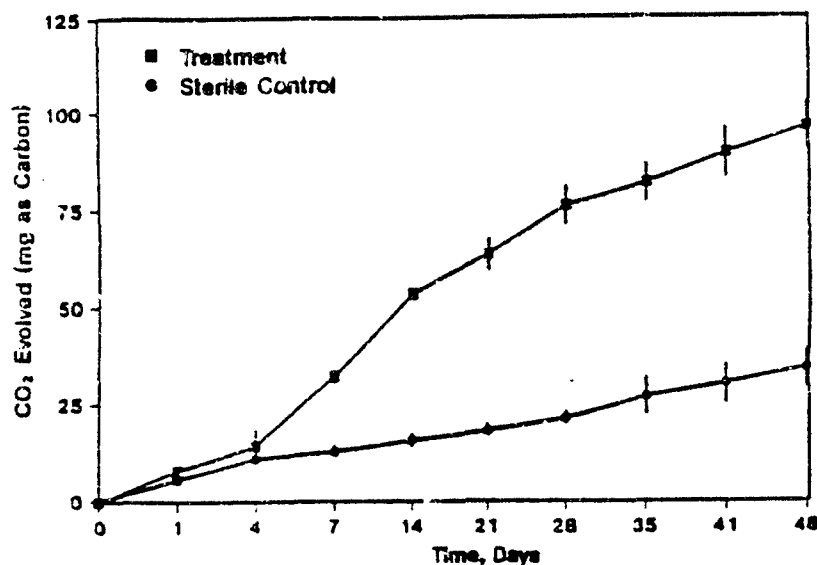


Figure 93. Results of Dead Control for Bench Scale Treatability Studies with Hill AFB, Utah, Soils. (The points are the means of two tests with the ends of the bars representing the results of such separate test. Both live and dead treatments are with 2% Restore 375 and at a moisture level of 50% of field capacities.)

of field capacity. Carbon dioxide evolution was substantially higher with the live treatment. The  $\text{CO}_2$  evolved by the dead control was most likely inorganic in nature released by the soil or water. The soil columns held at 75 percent of field capacity and amended with Restore<sup>®</sup> 375 evolved an average of  $115 \pm 6.1$  mg (460 mg/kg of column soil) of  $\text{CO}_2\text{-C}$  over 48 days. The next greatest average evolution of  $\text{CO}_2\text{-C}$ ,  $96.2 \pm 6.1$  mg, (385 mg/kg of column soil) was from the nutrient-amended columns held at 50 percent of field capacity. Finally, the nutrient-amended columns held at 25 percent field capacity averaged  $80.8 \pm 1.0$  mg of  $\text{CO}_2\text{-C}$  (323 mg/kg of column soil). All remaining columns, including the sterile controls, averaged 25 to 30 mg of  $\text{CO}_2\text{-C}$  over the 48-day incubation. The addition of nutrients appeared to stimulate respiration as measured by  $\text{CO}_2$  evolution.

Table 17 illustrates the results of hydrocarbon and microbial analysis before and after the 48-day treatability test. The variability inherent in these measurements make it difficult to discern trends with such a limited number of samples; however hydrocarbon concentrations were generally lower and microbial activity was higher after aeration.

## 6. Conclusions of Biodegradation Studies

Based on this study, the following conclusions are drawn:

1. Aerobic biodegradation of JP-4 did occur in the vadose zone at the Hill AFB site.

TABLE 17. RESULTS OF JP-4 HYDROCARBON ANALYSIS AND MICROBIAL ENUMERATIONS ON SOILS FROM THE BENCH SCALE TREATABILITY TESTING OF THE HILL AIR FORCE BASE SOILS. ALL RESULTS WERE THE MEAN OF TWO TREATMENTS.

TREATMENT	JP-4 HYDROCARBON CONCENTRATION (mg/kg)	HYDROCARBON DEGRADERS	
		TOTAL	(CFU/gm x 10 <sup>4</sup> )
Initial	1000	7.6	8.7
Dead Control	714	<0.001	<0.001
Without Nutrients			
25 Percent Field Capacity	282	1540	1160
50 Percent Field Capacity	374	860	1780
75 Percent Field Capacity	301	1510	1550
With Nutrients			
25 Percent Field Capacity	560	105	0.73
50 Percent Field Capacity	405	1350	478
75 Percent Field Capacity	371	4930	3170

2. Biodegradation was increased by the soil venting.

3. Laboratory bench scale studies indicate that it is feasible to substantially increase *in situ* biodegradation by the addition of inorganic nutrients and increasing soil moisture.

#### 7. Recommendations

The recommendations that result from this study are combined into two groups. The first is for those currently involved in soil venting who wish to document biodegradation at their sites, and the second group is to assist in the pursuit of a mature technology based upon these findings.

##### a. Recommendations for Conventional Soil Venting

Soil venting alone, with no nutrient addition or moisture addition, may result in stimulating *in situ* biodegradation. In this study it was found that about 15 percent of the JP-4 removal was the result of biodegradation. Ely and Heffner (Reference 29) report that at a gas line contaminated site,

2.3 percent  $O_2$ , 11 percent  $CO_2$ , and 4.9 percent oil vapor was observed in the venting site. At a background location they report 18.3 percent  $O_2$ , 1.0 percent  $CO_2$ , and 0 percent oil vapor. It is not clear if the background location was being vented, or what the duration of the venting was at the contaminated site; however, these data appear to indicate that higher biodegradation rates were observed than at the Hill Air Force Base site. Based upon this study, the following recommendations are made for those conducting conventional soil venting of fuel hydrocarbon-contaminated soils:

- (1) Before to venting, determine soil gas hydrocarbon,  $CO_2$ , and  $O_2$  profiles.
- (2) Measure hydrocarbon,  $CO_2$ , and  $O_2$  in the offgas. This information can be used to document biodegradation and may help determine the end point for venting. A mixed hydrocarbon fuel such as JP-4 has a fraction too heavy to volatilize, and biodegradation may continue after the light end has volatilized.
- (3) Develop an estimate of noncontaminant respiration. This may be done either through background measurements of  $CO_2$  and  $O_2$  in an uncontaminated location or by carbon isotopic analysis.

#### **b. Recommendations for Future Studies**

To further pursue the development of a soil-venting based, enhanced *in situ* technology, the following recommendations are made:

- (1) Further studies of fuel degradation in unsaturated soils are needed to develop a better understanding of variables such as oxygen content, nutrient requirements, soil moisture, contaminant levels (both high end for possible toxic effects and low end for treatment limits) and soil types.
- (2) Further studies of gas transport in the vadose zone are needed to allow adequate design of air delivery system.
- (3) Investigation of nutrient and moisture delivery systems, including possible gaseous nutrient injection [i.e., ammonia ( $NH_3$ )], means of engineering moisture addition in deeper stratified formations, and nutrient formulations to allow adequate nutrient mobility in pore water.
- (4) Investigation of alternative gas injection and withdrawal systems to optimize biodegradation and minimize volatilization, thereby avoiding problems associated with hydrocarbons in the soil gas. Alternatives include reducing gas flow rates to those necessary to maintain aerobic conditions and minimize hydrocarbon in the offgas, and configuring vents to allow injection of gas in the contaminated zone and extraction of gas from a more remote uncontaminated location thereby allowing biodegradation of hydrocarbons in the vapors and eliminating offgas treatment.

#### **8. Additional Observations by ORNL Staff**

Data on gas extraction, oxygen depletion, and carbon dioxide production through 15 April 1989 are included in Appendix D and Figure 94. These data indicate that the estimated



biodegradation continued to be about 18 percent. The estimates of hydrocarbon degradation from the oxygen depletion and carbon dioxide production are certainly comparable, and even in reasonable agreement, considering the various other uncontrolled and unmeasured phenomena that may be affecting the oxygen and carbon dioxide data.

#### F. SOIL MOISTURE

The moisture content of soil has a large impact on the air permeability of the soil (see Volume II). Soil moisture content may also affect biodegradation rates and partitioning of hydrocarbons between phases. Soil venting may reduce the moisture content of the soil, as drier atmospheric air is pulled through the soil. The humidity measurements of the extracted soil gas remained within the 90 to 100 percent relative humidity range throughout the demonstration; thus, there was potential for drying of the soils, especially near the surface. Neutron absorption measurements were made to investigate the changing moisture profiles during the venting operations.

As detailed in Section V.B, three neutron access tubes (NATs) were installed at the site and were logged prior to, during (four times), and following the venting operation to assess changes in soil moisture caused by the venting operation. The tubes were installed at the following locations to assess the effect of the surface barrier

NA1: Vented area, no surface barrier

NA2: Vented area, covered by surface barrier

NA3: Outside main zone of venting (i. e., control tube)

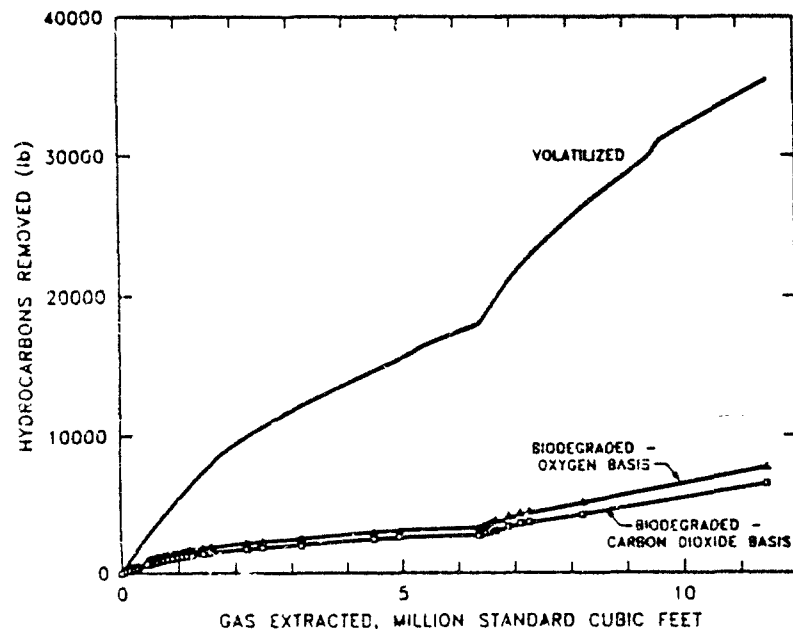


Figure 94. Comparison of Hydrocarbon Removal by Biodegradation and Volatilization.

Logging data from the three tubes are tabulated in Appendix E. Moisture levels ranged from 0.2 percent (at the surface of NA1 in August 1989) to a maximum recorded value of 60.4 percent (NA2 Jan 1989). The latter apparently is an anomaly, possibly caused by a neutron-absorbing material near the surface (such as oil) which would yield an erroneously high reading.

The June 1989 logging results are shown for each NAT in Figures 95 through 97. In many respects these data are representative of the entire set of measurements. Moisture levels throughout most of each NAT are 8 to 11 percent, with discrete zones of moisture present apparently at near-saturation values. Elevated moisture levels are seen at depths of 12, 25, and 31 feet (3.7, 7.6, and 9.4 meters) BLS in NA1; at 10 and 23 feet (3.0 and 7.0 meters), and throughout the 39 to 45 foot (11.9 to 13.7 meters) interval in NA2; and at 24, 32, and 39 to 40 feet (7.3, 9.8, and 11.9 to 12.2 meters) in NA3. The zones of high water content do not coincide in the three tubes, reflecting discontinuities in the clay layers as was observed in the borehole logs.

The log of NA2 may be compared to the moisture analyses of vent borings V9 and V10 which are located within 10 feet of NA1. The NAT readings are generally 4 to 8 percent higher than the moisture analyses (although the V9 and V10 borings may not be exactly representative of the NA1 borehole). More importantly, however, the comparison suggests that relative variations in NAT log readings accurately reflect changes in soil moisture with depth.

The pattern of soil moisture at the venting site is illustrated in Figure 98 which shows the profile of moisture in NA1 at four times: prior to venting (16 September 1988), during the initial stage of venting (12 January 1989), about midpoint in the venting process (8 June 1989), and following termination of venting (12 October 1989). Moisture profiles for the four dates are virtually indistinguishable below a depth of 10 feet (3.0 meters) in all of the NATs. Clearly the venting process had no discernable effect on soil moisture below the 10-foot depth. In the upper 10 feet a similar pattern was seen in all 3 NATs: (1) soil moisture increased between September 1988 and January 1989; (2) declined in the upper 2 feet (0.6 meters) between January 1989 and June 1989 but remained nearly constant below 2 feet during that period; and (3) declined to near-zero in the upper foot of soil, and to reduced levels within the upper 10 feet, by October 1989. Because this pattern appeared in all 3 NATs, it appears to be unrelated either to venting or to the presence or absence of the vapor barrier, and was probably caused by recharge of soil water from rainfall and snowmelt during late winter and early spring, followed by desiccation of the upper soil zone by heat and low humidity during the summer. The October 1989 data indicate that soil moisture loss may extend deeper in NA1 and NA2 than in NA3, suggesting that venting may have contributed to water loss from the upper soil zone, but the difference [8 feet versus 5 feet (2.4 versus 1.5 meters)] is too small to draw a definite conclusion.

## G. FLOW TESTS AND MODELING

As noted in Volume I, the amount and geometry of gas flow relative to contamination are the two most important factors in the effectiveness of *in situ* soil venting. The simulations presented in Appendix K (unpublished - available from ORNL and AFESC) and in Volume II illustrated that the configuration of operating vents may have a large effect on the distribution of air flow in the soil; thus, an understanding of the flow patterns induced by various vent configurations will be valuable in optimizing system design and operation. In an effort to advance the understanding of this subject, a series of flow tests was conducted to collect field air flow data. The results will be useful both for

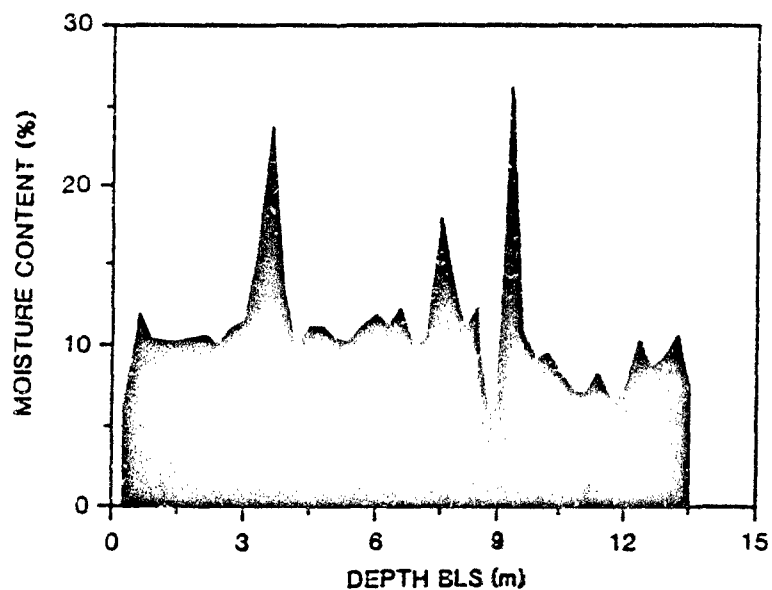


Figure 95. Depth Profile of Moisture Content in Neutron Access Tube (NA 1) Installed in Vented Area Without Surface Cover, June 1989.

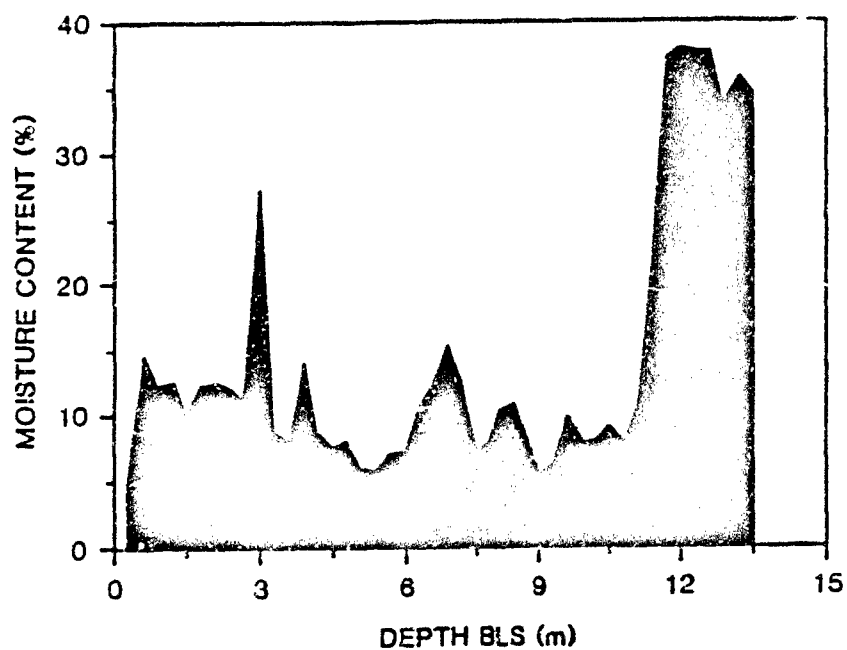


Figure 96. Depth Profile of Moisture Content in Neutron Access Tube (NA2) Installed in Vented Area With Surface Cover, June 1989.

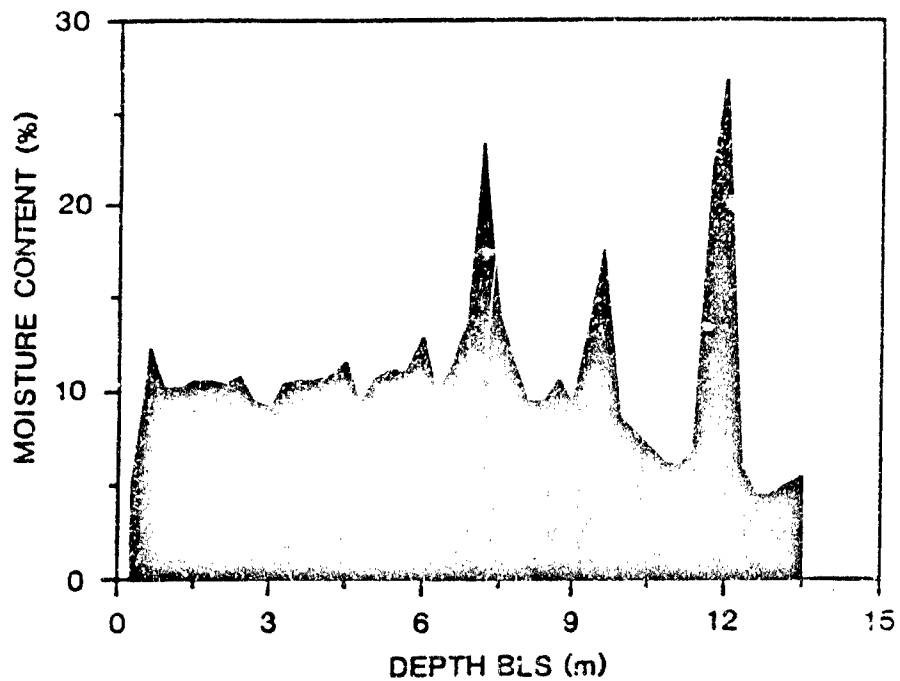


Figure 97. Depth Profile of Moisture Content in Neutron Access Tube (NA 3) Installed Beyond the Vented Area, June 1989.

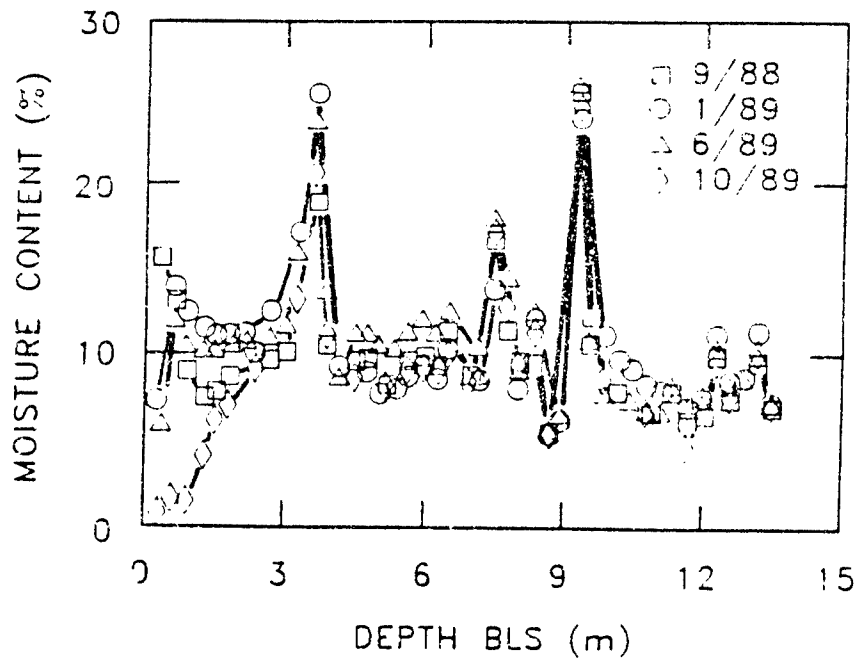


Figure 98. Depth Profiles of Moisture Content Recorded in NA 1 at Four Dates Prior To, During, and Following the Venting Demonstration.

analysis of flow patterns achieved with different operating strategies and for verification of flow models which may be used in further study and design.

This section describes the flow tests and presents selected results. Additionally, a flow modelling study is presented in Appendix K (unpublished - available from ORNL and AFESC), which includes development of an analytic flow model and compares simulations by the analytic model and the FEMAIR numerical model with single vent flow test results.

### 1. Flow Test Description

A total of 40 vent configuration tests were conducted during the full-scale demonstration. These tests consisted of setting the extraction and passive inlet rates for a given set of vertical or lateral vents, allowing the system to reach steady-state (as evidenced by unchanging pressure readings in the soil), and measuring the induced vacuum at each pressure monitoring point and vent.

The test conditions for each of the tests are given in Table 1 of Appendix F, which lists the extraction and injection flows at each vent. Vent tests in the vertical vent system (with extraction only) included single vent tests inside and outside the area of the surface barrier, multiple vent tests with a linear well configuration, and grid configurations inside and outside the area of the surface barrier. Tests with inlet vents were conducted for a single vent, two vents, and one grid. Vent tests in the lateral vent system include a single extraction vent, a single extraction vent with two inlet vents, and three extraction vents with and without three inlet vents.

These tests provide a large data base of flow measurements in field conditions at a well-characterized site.

### 2. Flow Test Results

The results of each of the flow tests are listed in Table 2 of Appendix F. The information included are the coordinates (N-S, E-W, and depth) of all vents and pressure monitoring points and the steady-state vacuum for each point in the tests. The set of results provide a suitable basis for detailed study of many aspects of single and multiple vertical vent operation such as: with and without a surface barrier, with and without passive inlet vents, and single and multiple lateral vent operation with and without passive inlet vents.

The results discussed in the paragraphs below depict gross flow behavior of multiple vertical vents. Appendix K (unpublished - available from ORNL and AFESC) describes in detail a modeling study of single vertical vent operation. A detailed study of the multiple vertical vent or lateral vent data was not completed within this effort.

Figures 99-102 present isobars (vacuum levels measured in inches of water) calculated by contouring pressure data of four selected flow tests. Only pressure measurements taken at the vents were used in preparation of these plots. Since the vents have a long screened section [40 feet (12.2 meters)], the contours provide a depiction of the depth-averaged pressure.

Figures 99 and 100 show the pressure distribution for single vents without and with a surface barrier, respectively. Figure 99 presents steady-state vacuum levels induced at the vents for extraction

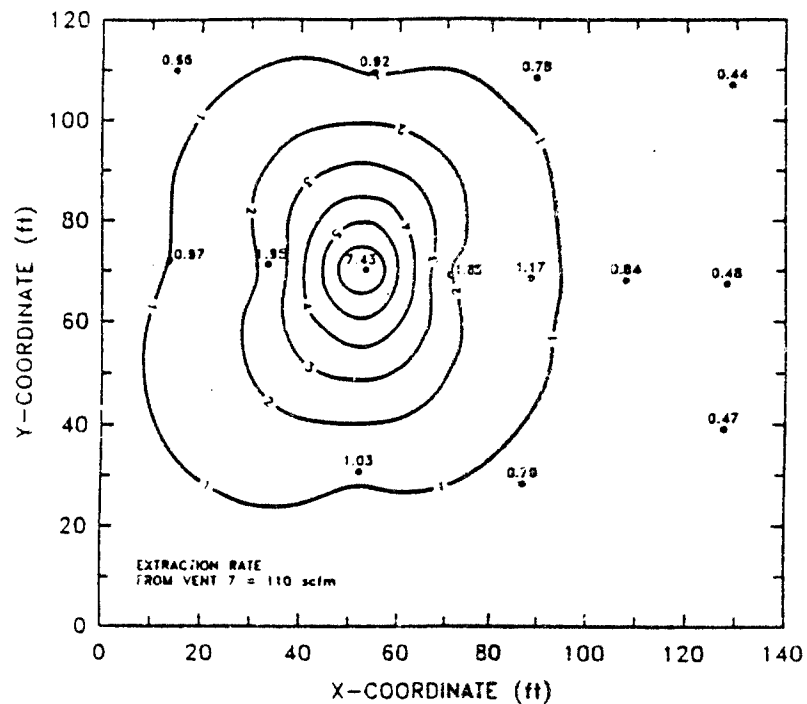


Figure 99. Depth-Averaged Pressure Contours - Flow Test 3.

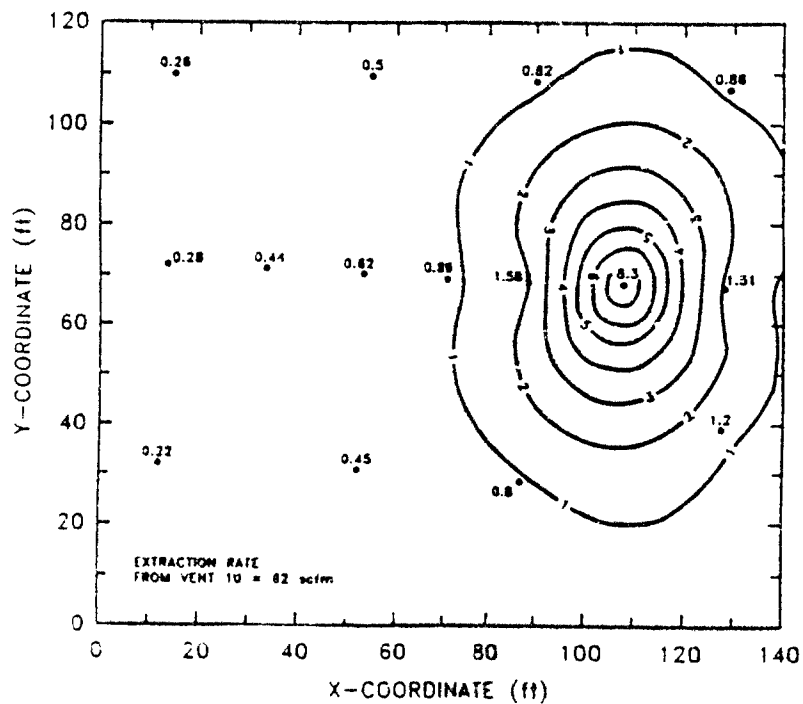


Figure 100. Depth-Averaged Pressure Contours - Flow Test 4.

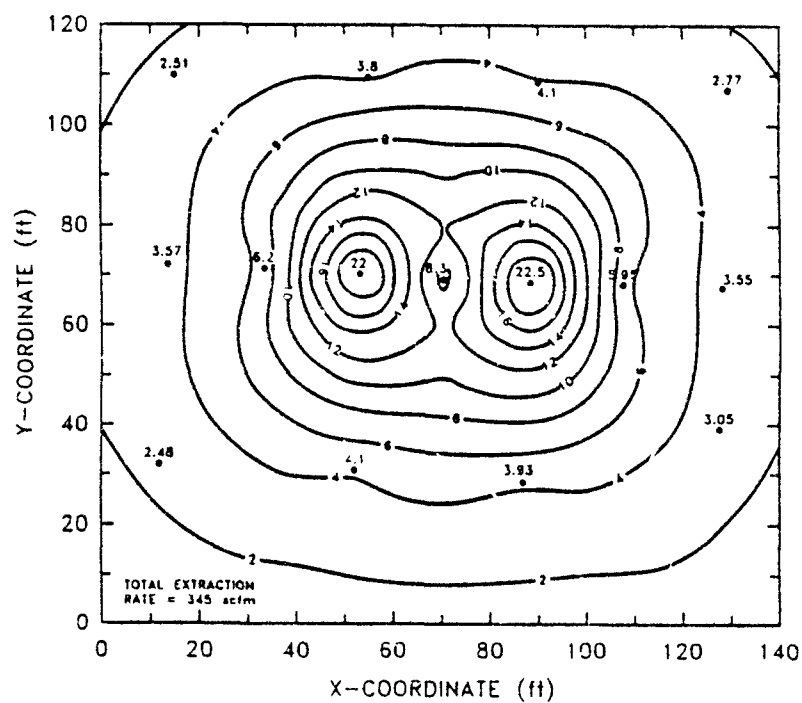


Figure 101. Depth-Averaged Pressure Contours - Flow Test 15.

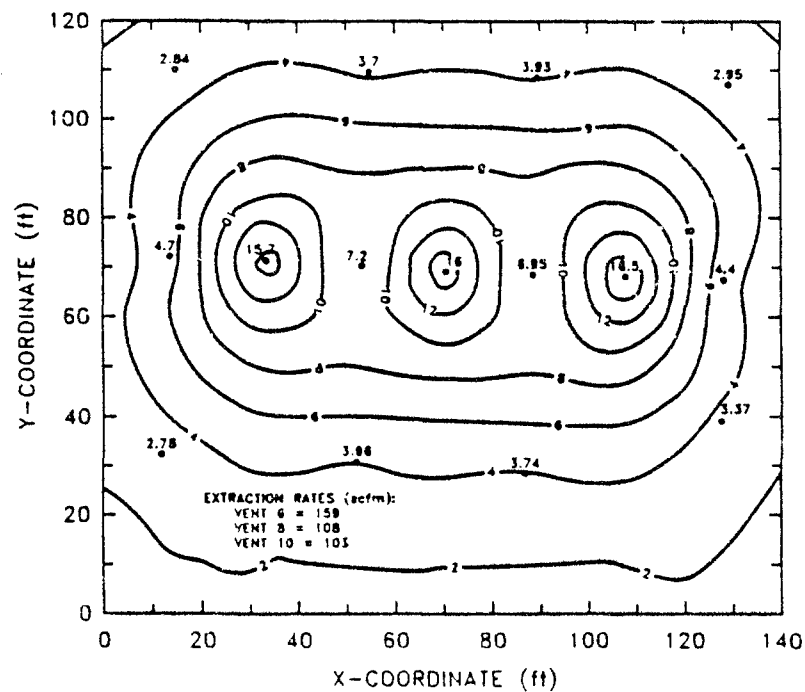


Figure 102. Depth-Averaged Pressure Contours - Flow Test 22.

of 110 scfm (0.052 standard m<sup>3</sup>/second) from Vent 7 and Figure 100 presents results during extraction of 62 scfm (0.029 standard m<sup>3</sup>/second) from Vent 10. Although the plots are similar, it may be noted that greater vacuum was necessary to induce less flow in the barrier case. Relatively large zones of influence based on pressure are noted in both cases.

Figures 101 and 102 show pressure results for multiple vent operations. Figure 101 shows the results for extraction of a total of 345 scfm (0.16 standard m<sup>3</sup>/second) from Vents 7 and 9 and Figure 102 shows results obtained during extraction of a total of 370 scfm (0.17 standard m<sup>3</sup>/second) from Vents 6, 8, and 10 (159 scfm from Vent 6, 108 scfm from Vent 8, and 103 scfm from Vent 10). The contours show that, at a distance, the effects are similar in the 2- and 3-vent operations; however, near the vents the pressure distribution and flow differ. Again, less vacuum (and, thus, less blower power) is necessary for the same flow but with more operating vents.

A point of concern are the midpoints between operating vents. Although the midpoint vacuum levels are relatively high in these areas, they are located in zones of relatively low flow, since air flow is directed normal to isobars. Thus, it is expected that in test 22 (Figure 102) the area near Vent 11 is being treated at a faster rate than the area near Vent 9, even though the vacuum levels at the two vents are 4.4 inches of water (1100 Pascals) and 6.95 inches of water (1730 Pascals), respectively.

The complete data set provides measurements of pressure at different depths and positions, and could be used for comparison of pressure distributions as well. For instance, the pressure results of similar tests within and outside the surface barrier (such as flow tests 24 and 26) show greater vertical pressure variation and thus a greater vertical flow component in cases with no barrier.

### 3. Air Flow Modeling

Preliminary modeling suggested that, without a surface barrier, much of the flow would be from the surface immediately surrounding the extraction vent to the vent screen, with little horizontal flow through the contaminated soil. Additionally, stagnant zones were predicted for multiple-vent operations. The purpose of the modeling effort described here was to compare model predictions for cases with and without a surface barrier with the data collected at Hill AFB, to determine the effectiveness of the surface barrier and the models' ability to predict the measured vacuum. Because of time and budget constraints, only two of the flow tests were modeled. Both were steady-state, single-vent extraction runs, one with an impermeable ground cover surrounding the extraction vent, the other without any surface cover.

Two types of models were used: an analytic solution based on the Method of Images, and the finite element program FEMAIR. These models, the assumptions implicit in their use, and the model predictions are discussed in Appendix K (unpublished - available from ORNL and AFESC). The conclusions of the modeling work are discussed briefly below.

With all other conditions held constant, the analytic solution and the numerical model both predicted a greater vacuum in the soil when the surface is covered. This is not surprising, without a surface cover one would expect air to be drawn vertically from the surface in the vicinity of the vent with little horizontal flow. However, the data from the flow tests with and without a surface barrier is nearly the same, generally falling between the model predictions for covered and uncovered cases.



One possible explanation is that water in the near-surface sediments reduced the relative permeability, creating a semi-confining layer. There is some evidence for this in the *in situ* moisture measurements. It is interesting to note that the pressure data for deeper monitoring points agreed better with the confined model predictions than did the data for shallower points. Thin clay layers were encountered in many of the boreholes during site characterization; the cumulative effect of these layers may be a decrease in average vertical air permeability with increasing depth.

In conclusion, presence or absence of a surface cover seems to have had little effect on the air flow at the Hill AFB site for single-vent operation. The effect of the surface cover during multiple vent operation was not investigated by flow modeling. The data from the two tests studied suggest that the flow is at least partially confined via natural phenomena. The source of this natural reduction in vertical permeability may be related to surface moisture and thin clay layering. Further modeling, comparisons with other test data, and additional field work (such as measurements of permeability as a function of depth) would be required to confirm this hypothesis.

## H. ENHANCEMENT OF REMOVAL BY HEATING

### 1. Concept

Generally accepted qualitative limits for applicability of soil venting are contaminants having a vapor pressure of greater than 0.5 mm Hg (66 Pascals) and a soil air permeability of greater than  $10^{-10}$  cm<sup>2</sup> (see Volume I). However, since these limits are based upon the rate of removal of contaminants, the above limits may be extended, and applications well within the limits hastened, if removal rates may be increased by either shifting equilibrium conditions to higher contaminant vapor concentrations or by accelerating transport rate processes.

One potential means for enhancing removal rates is elevation of soil temperature. Johnson and Sterrett (Reference 20) noted increased removal rates of 1,3-dichloropropane in field conditions with higher ambient temperatures. Higher temperature will affect equilibrium conditions by increasing contaminant vapor pressures and Henry's Law coefficients and by generally causing desorption of contaminants from the soil. Diffusive/convective transport may also be somewhat affected by an increase in diffusivity and by changes in air permeability (mainly due to changes in soil moisture content).

Of these effects, it is expected that the variation of vapor pressure will provide the largest contribution to enhancement by heating. Table 18 shows the profound effect of temperature on the vapor pressure of some selected compounds, as predicted by the Antoine equation (Reference 18).

This vapor pressure effect could be used to accelerate the timetable of cleanup, as shown in Figure 103. The curves in this figure, displaying the fractional amount of contaminant remaining as a function of cumulative air contacted per mass of initial contaminant present, were derived from a Raoult's Law equilibrium model for removal of JP-4 jet fuel at soil temperatures of 50, 75, and 100°F (10, 24, and 38 °C). For an ideal case of homogeneous air/contaminant contact and equilibrium conditions, 80 percent removal of JP-4 would be achieved through contact of approximately 50 standard liters of air per gram of JP-4 at a soil temperature of 100°F, while approximately 430 liters of air per gram of JP-4 is necessary for the same removal at 50°F.

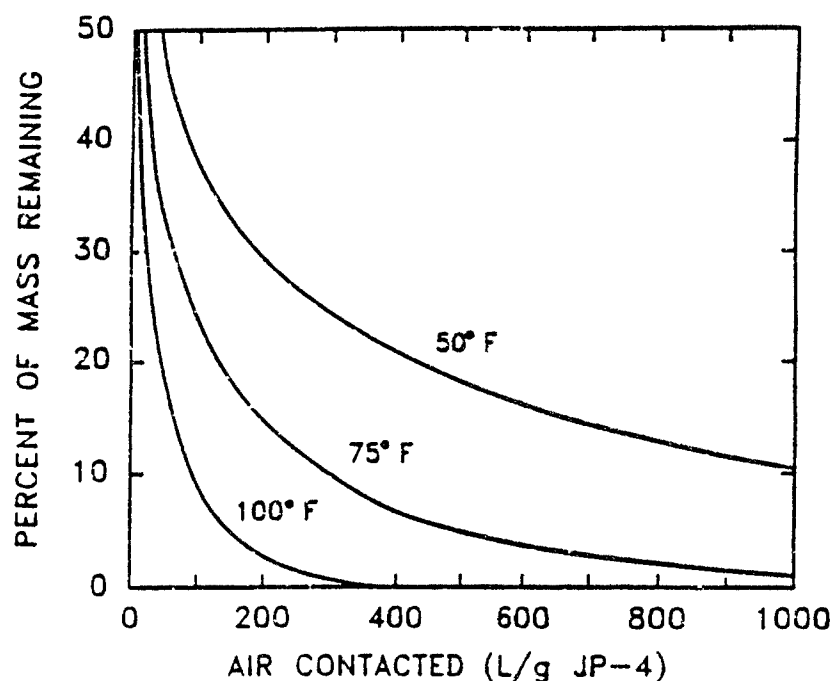


Figure 103. Equilibrium Removal Curves for JP-4 Standard Showing the Effect of Temperature.

Table 18. VARIATION OF VAPOR PRESSURE (IN MILLIMETERS OF MERCURY) WITH TEMPERATURE FOR SELECTED FUEL COMPONENTS

	n-HEXANE	BENZENE	TOLUENE	m-XYLENE	n-OCTANE
50°F	76	46	12	3.2	5.6
75°F	140	90	27	7.8	13
100°F	260	170	53	17	28
Vapor Pressure Ratio 100°F:50°F	3.4	3.7	4.3	5.3	5.0

Therefore, the cleanup using heat enhancement could be performed in 10 percent of the time of the non-heated case. Alternatively, greater than 99 percent removal could be reached at 100°F in the same time necessary for 80 percent removal at 50°F.

Due to the potential enhancement of extraction rates with increased temperature, several authors have suggested means for raising soil temperatures. Anastos et al. (Reference 5) abandoned plans to heat inlet air by electrical means due to the higher energy requirements for appreciable enhancements. Johnson et al. (Reference 17) suggested radio frequency and conduction heating or

injection of exhaust from combustion units. Steam injection has also been mentioned for heating the soil, both in soil venting and in an agitated soil air stripping technique (Reference 30). It should be noted that steam injection may be less attractive due to the detrimental effect of moisture in reducing air permeability and the possibility of dissolution and contaminant transport. However, for very dry soil, moisture may enhance desorption of chemicals from the soil particles.

Obstacles to overcome in implementing a heat enhancement strategy include supplying the vast quantity of energy necessary to heat the soils containing the contaminants to the elevated temperature and developing methods for delivering the heat evenly and inexpensively. As an illustration of the magnitude of the heating load required, consider soil having a dry density of 100 pound/ft<sup>3</sup> (1600 kg/m<sup>3</sup>) and heat capacity of 0.2 BTU/pound°F (837 J/kg°C). The temperature of a cubic foot (0.028 m<sup>3</sup>) of dry soil would rise 1°F (0.56 °C) with a heat input of 20 BTU (21,100 J). If the soil contained 5% moisture by weight, the same soil volume would require 25 BTU (26,400 J) for the same temperature rise. One standard cubic foot (0.028 standard m<sup>3</sup>) of air cooling from 1000°F to 68°F (538°C to 20°C) supplies 18.7 BTU (19,700 J), whereas 1 pound (0.454 kg) of steam condensing at 212° (100°C) and cooling to 68°F (20°C) supplies 1115 BTU (1.18 x 10<sup>6</sup> J). For the Hill AFB site, a contaminated soil volume of approximately 720,000 ft<sup>3</sup> (20,400 m<sup>3</sup>) required treatment. Thus, assuming adiabatic conditions,

$$\left(25 \frac{\text{BTU}}{\text{ft}^3 \text{ } ^\circ\text{F}}\right) 720,000 \text{ ft}^3 (25^\circ\text{F}) = 450 \times 10^6 \text{ BTU} = 4.74 \times 10^9 \text{ J} \quad [20]$$

would be necessary to raise the entire soil volume 25°F (13.9°C). If this were supplied by air cooling from 1000°F, as described above,

$$\frac{450 \times 10^6 \text{ BTU}}{18.7 \text{ BTU/ft}^3} = 24 \times 10^6 \text{ std ft}^3 = 6.82 \times 10^5 \text{ std m}^3 \quad [21]$$

air volume is required, which, at a 1000 scfm (0.47 standard m<sup>3</sup>/second) injection rate corresponds to 16.7 days. Steam injection as described above would entail

$$\frac{450 \times 10^6 \text{ BTU}}{1115 \text{ BTU/lb steam}} = 400,000 \text{ lb} = 181,000 \text{ kg} \quad [22]$$

of steam to raise the soil temperature 25°F (13.9°C). In the process, the average soil moisture content would increase from 5 percent to 5.5 percent. However, local moisture levels, particularly in the vicinity of injection points could be much higher, possibly significantly decreasing air permeability. (The effect of permeability on injection flow may be insignificant, however, due to the steam pressures achievable to drive flow.) Also, the additional 400,000 pounds (181,000 kg) of water would be available for dissolution of hydrocarbons and possible transport by percolation to the saturated zone.

The above rough calculations neglect heat losses, which may be quite substantial. Although considerable energy demands are made, the increased removal rate may make heating of the soil an economical addition to venting systems in many cases. In order to investigate this concept, a test of heat injection was devised and conducted during the full-scale demonstration. The heat source for

this study was chosen to be the stack gas of the fixed-bed catalytic oxidation emissions control unit, from which heat was normally wasted to the atmosphere.

## 2. Description of Test

The system was constructed as shown in Figure 104. A tee was installed on the stack of the fixed-bed catalytic oxidizer, allowing the diversion of some of the stack gas to injection vents.

Carbon steel tubing of 5-inch (12.7-cm) nominal size was run approximately 350 feet (107 meters) to Vent 10, and an additional 75 feet (22.9 meters) to Vent 6. The tubing was covered with 1 inch (2.54 cm) of high temperature fiberglass insulation protected by aluminum sheet. These vents were constructed completely of 4-inch (10.2-cm) stainless steel well screen and riser pipe, since the PVC was rated to withstand temperatures only up to 140°F (60°C) in the presence of JP-4. Blanks were used at flanges at the well heads to isolate the wells from the heat injection line. No blower was installed in the heated gas line; rather, the test was designed to allow vacuum induced in the soil to pull the heated gas into the well.

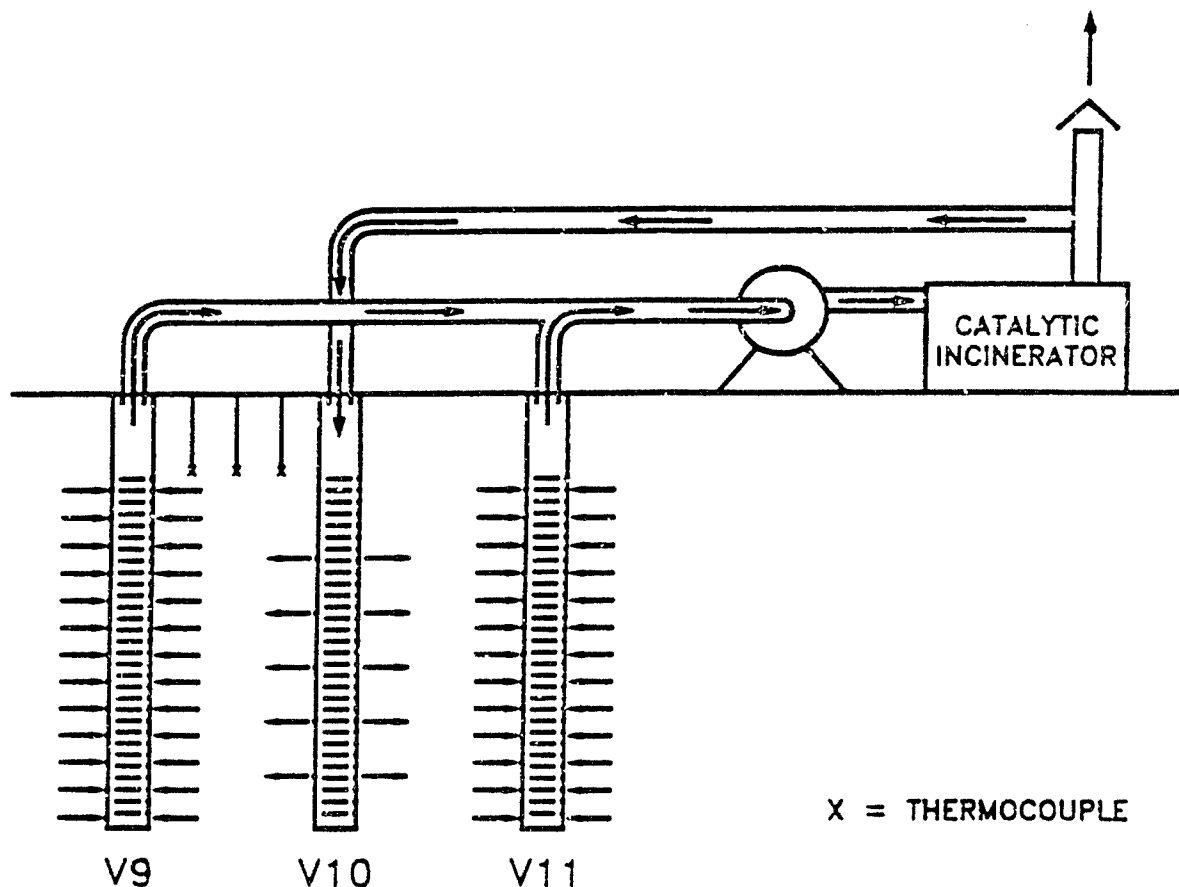


Figure 104. Schematic of Heat Injection Test System.

Thermocouples were installed in the well heads of Vents 9, 10, and 11 and in the soil in the positions shown in Figure 105. The thermocouples were placed in hand-augered holes at depths ranging from 10.9 to 13.5 feet (3.3 to 4.1 meters). Since this depth is near the top of the screened interval of the wells, the temperatures are likely to be less influenced than in the center of the affected zone.

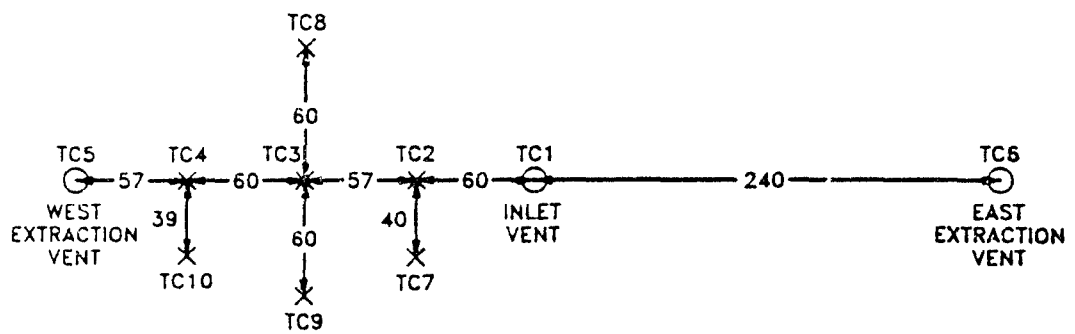
Temperatures and concentrations were read periodically from the thermocouples and THA as well as continuously recorded on a chart recorder and data logger. Samples of the extracted gas were taken periodically on sorbent for later GC analysis of the extracted gas. The effects of elevated temperatures upon bioactivity, which had proven to be significant in the earlier portion of the demonstration, could not be measured due to the high CO<sub>2</sub> concentration in the inlet gas.

Heat injection was begun on 16 August 1989 and continued to 7 October 1989 with a total extraction rate of 650 scfm (0.307 standard m<sup>3</sup>/second) and measured flows of 410 scfm (0.193 standard m<sup>3</sup>/second) from the Vent 9 and 240 scfm (0.113 standard m<sup>3</sup>/second) from Vent 11. In this configuration, a vacuum of 48 inches of water (11900 Pascals) was induced under static conditions at the inlet vent. Opening Vent 10 to the heat injection line induced an injection flow rate of 93 scfm (0.044 standard m<sup>3</sup>/second) at 1.7 inches of water (423 Pascals) vacuum. Vent 6 remained closed throughout the test.

### 3. Results

Operationally, the heat injection system ran quite well. However, due to heat losses in the piping, the inlet gas temperature was decreased from over 600° F (316° C) at the oxidizer stack to between 200 and 215° F (93 and 102° C) at the inlet vent. Water uptake in the extraction piping was also noted to be increased during the test in comparison to earlier operation, due to a combination of greater vacuum levels at the extraction vents [approximately 60 inches of water (14900 Pascals)] and to moisture content of the heated input air. No major changes in the flow rates or vacuum required were noted despite the increased moisture.

The results of temperature measurements from each of the thermocouples are presented graphically in Figure 106 as a function of time of the test. The temperature at each of the points in the soil appears to have reached steady state during the test. Thermocouples farther from the injection vent reached steady state slower than those closer to the injection vent, and reached a lower steady state temperature. This may be seen most clearly by comparison of temperatures at thermocouples 2, 3, and 4, which were placed 1/4, 1/2, and 3/4 of the distance along the line from the inlet vent to the west extraction vent. Thermocouple 2 reached a steady-state temperature of 98 to 100° F (36.7 to 37.8° C) in about 15 days, Thermocouple 3 reached steady state temperature of approximately 91° F (32.8° C) in about 23 days and Thermocouple 4 reached a steady state temperature of about 88° F (31.1° C) in 30 days. The progression of the temperature profile is also shown in the three frames of Figure 107, displaying the temperature (in °F) at the thermocouple positions at the start of the test, after 13 days, and after 36 days. It should be noted that all points except those corresponding to the vents indicate soil temperature, whereas the vent points (those points labeled with temperature values of 207° F at the inlet and 73° F at the west extraction vent in the bottom frame) indicate gas temperature.



NOTE:

Thermocouples TC1, TC5, and TC6 measured temperature of gas at vent head. All other thermocouples measured soil temperature at depths ranging from 11 to 13.5 ft below land surface.

Dimension are in inches.

Figure 105. Positions of Thermocouples for Heat Injection Test.

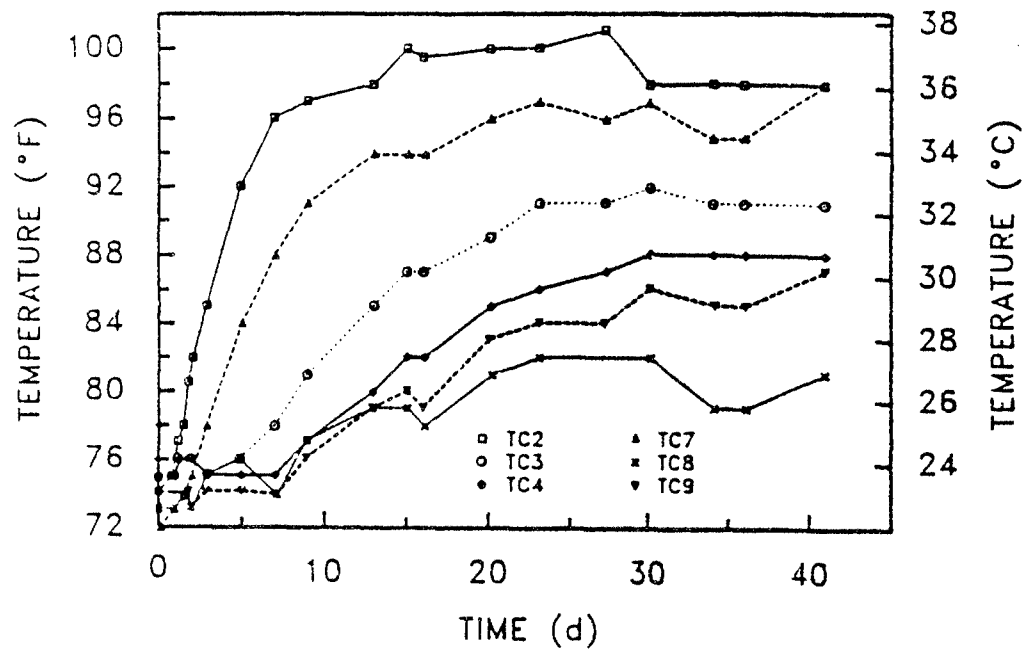


Figure 106. Variation of Soil Temperature Measurements During Heat Injection Test.

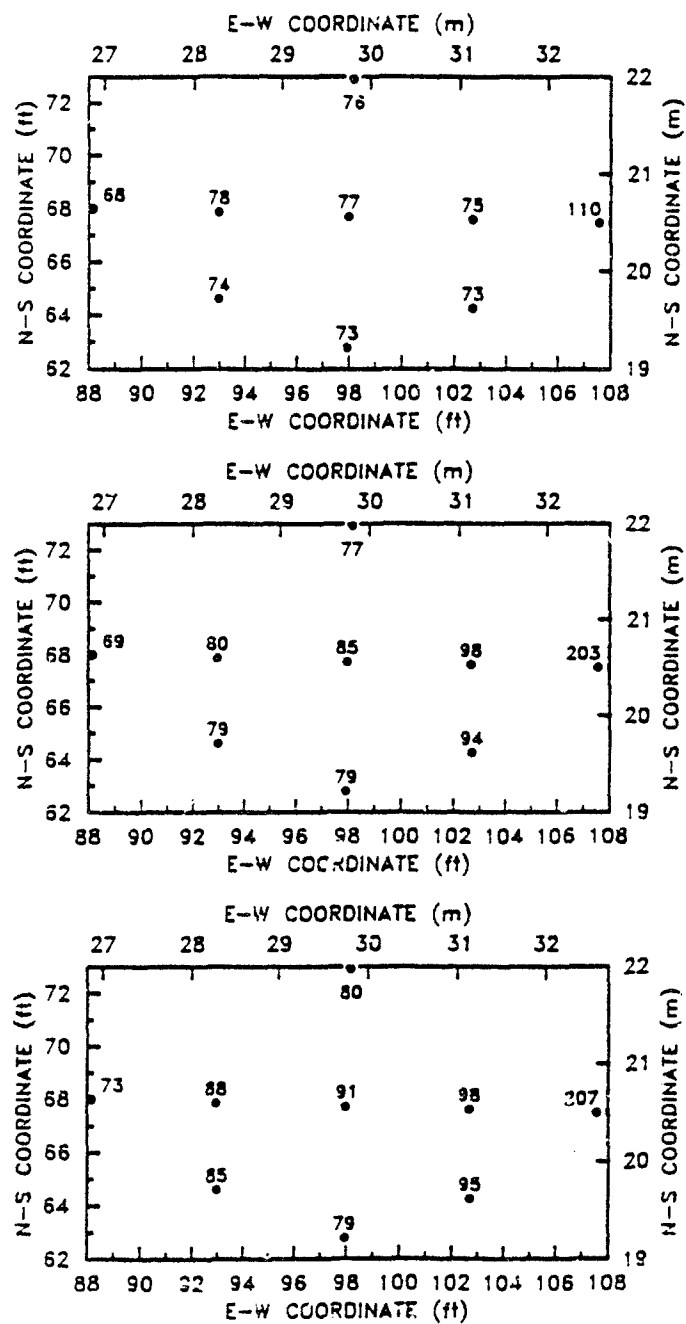


Figure 107. Areal Distribution of Temperatures at Three Times During Heat Injection Test - 16 August 1989, 29 August 1989, and 21 September 1989.

Hydrocarbon concentrations in the extracted gas are displayed in Figure 108 as ppm hexane equivalent total hydrocarbons as a function of cumulative standard cubic meters (and standard cubic feet) of gas extracted during the entire demonstration. The heat injection test commenced at the  $127 \times 10^6 \text{ ft}^3$  ( $3.60 \times 10^6 \text{ m}^3$ ) mark. The upper points are from THA measurements, whereas the lower points were calculated from GC samples taken from each extraction vent. The GC results remained lower than THA results. The two sets of results display a common trait in the general shape of the curves. Each showed a consistent decrease in concentration until the 155 to 160 million cubic feet (4.39 to 4.53 million cubic meter) range. At this point (approximately 12 September through 15 September, or 27 to 30 days into the test), roughly the point at which the farthest soil thermocouples reached steady state temperatures, the concentration in the extracted gas is seen to markedly increase. This concentration increase qualitatively correlates with the temperature front approaching the extraction vent. The nearly constant measurement of concentration by the THA from 157 to 167 million standard cubic feet (4.45 to 4.73 million cubic meters) is postulated to be due to a balance of two factors, one being higher gas concentration because of increased temperature and the other being decreased gas concentration due to decreasing soil contaminant concentration and change in composition to a heavier hydrocarbon mixture.

An estimate of the removal enhancement by heat injection can be made by analysis of the data as shown in Figure 109. In this analysis, the THA data is used because of a greater number of points and less scatter. The 12 data points from  $127 \times 10^6$  to  $154 \times 10^6 \text{ ft}^3$  ( $3.60 \times 10^6$  to  $4.36 \times 10^6 \text{ m}^3$ ) were fitted with a straight line which appears to be valid over this limited range. This line is extrapolated to estimate the non-heating volatilization. Another line was regressed to the four points from  $157 \times 10^6$  to  $167 \times 10^6 \text{ ft}^3$  ( $4.45 \times 10^6$  to  $4.73 \times 10^6 \text{ m}^3$ ). The integrated difference between these two lines, as shown by the shaded area in Figure 109, is the calculated removal enhancement due to heating. From  $4.45 \times 10^6$  to  $4.73 \times 10^6 \text{ m}^3$ , 540 pounds (245 kg) is the quantity that would be expected to be removed in the absence of heating by extrapolation of the straight line trend. The upper line indicates that approximately 920 pounds (417 kg) were removed during the period. The difference is 380 pounds (172 kg), or an increase of 70%. The removal increase over the entire period of the test, from  $127 \times 10^6$  to  $167 \times 10^6 \text{ ft}^3$  ( $3.60 \times 10^6$  to  $4.73 \times 10^6 \text{ m}^3$ ) extracted is 8.9%, 4690 pounds (2127 kg) actual and 4310 pounds (1955 kg) expected without heating. It is obvious that this ratio would increase with further operation. Only limited soil sampling was performed in the soil zone of the heat injection test after the demonstration, so little can be inferred as to the transport of contaminant with the temperature profile.

#### 4. Discussion

The results of this test of enhancement of removal with soil heating must be treated with care in predicting the effectiveness of the technique in other site applications. The most obvious measures of performance in this test are the 8.9% and the 70% values obtained above. However, these values are artifacts of the length of the test - for instance, if the test were only operated for a period during which the heat front had not reached the extraction vents, the enhancement value would have been 0%. Likewise, if the test had been conducted for a longer period, a value of much greater than 8.9% would have been obtained, perhaps on the order of the 70% enhancement measured in the period after the development of the steady-state temperature profile.



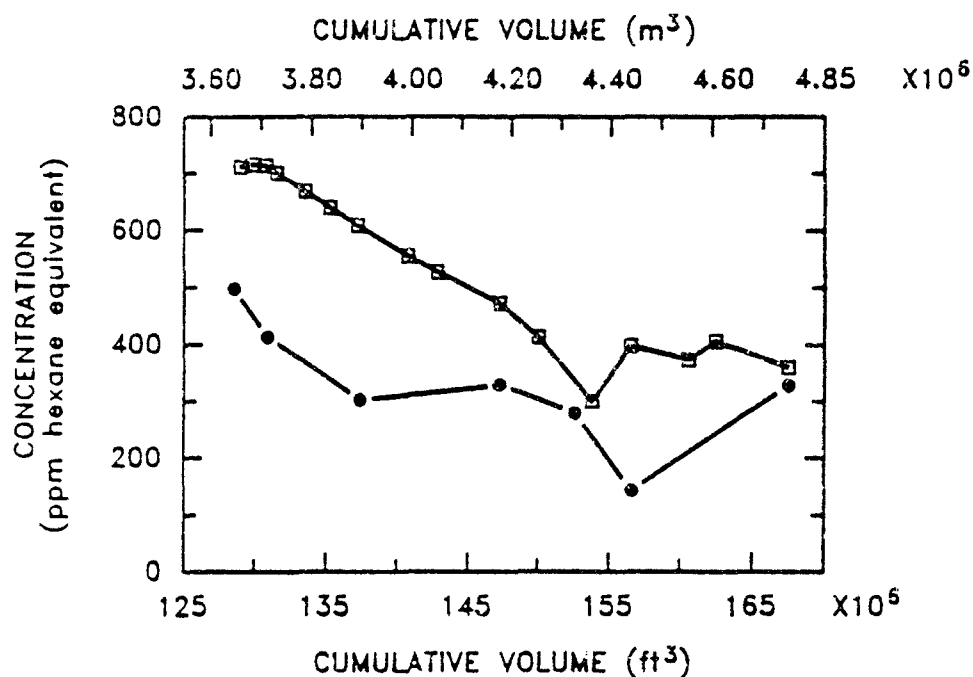


Figure 108. Hydrocarbon Levels in Extracted Gas During Heat Injection Test. (□ = THA measurements; ● = GC measurements.)

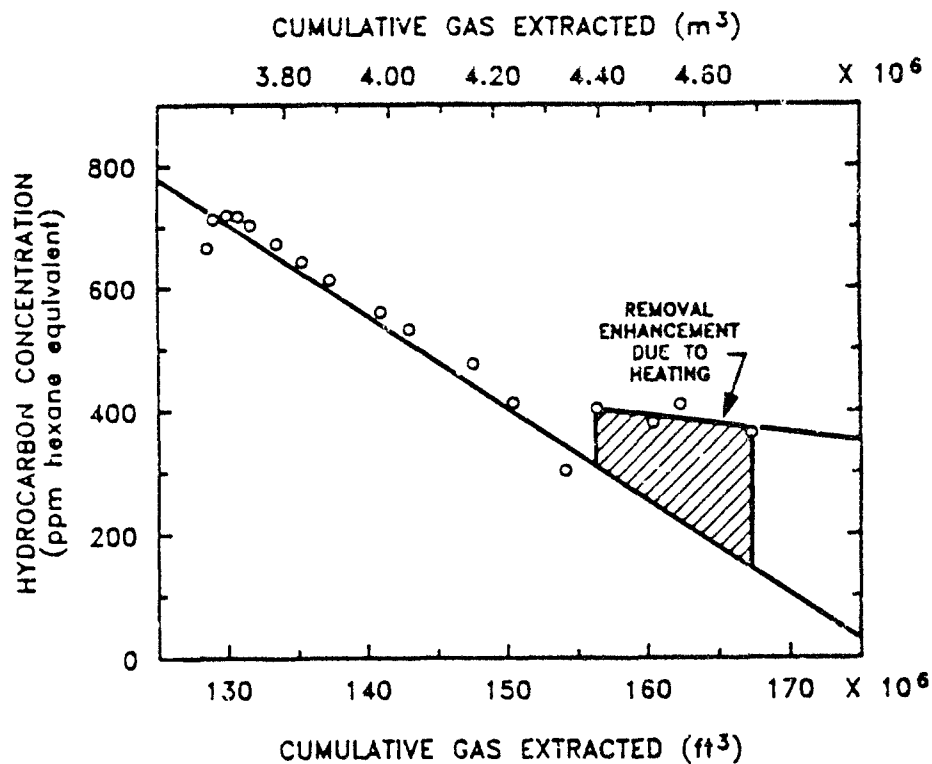


Figure 109. Calculation of Removal Enhancement by Heating.

Another test condition which had a significant effect upon the measured removal enhancement was the ratio of the inlet air rate to the extraction rate. Hydrocarbons were extracted from soil zones which were not contacted with the heated air as well as from the soil zone of interest. Indeed, since the inlet air amounted to a small fraction of the extraction flow rate, the majority of the hydrocarbon extraction could be assumed to be relatively unaffected by the heated air flow. Upper bounds on the achievable enhancement for this test could be estimated by assuming homogeneous contaminant distribution in the soil and negligible heat conduction. With these assumptions, the hydrocarbon removal may be split proportionally by air flow ratios into two portions: that affected by heating and that unaffected by heating. In this approach, of the 4310 pounds (1955 kg) that were expected to have been removed over the entire test period, 620 pounds (281 kg, as calculated by  $(4310 \text{ pounds} \times 93 \text{ scfm inlet rate} / 650 \text{ scfm extraction rate})$ ) would have been extracted from the soil zones affected by the heated air. Therefore, 3690 pounds (4310 - 620 pounds) would be extracted from outside the heated zone regardless of whether heat was applied or not. Therefore, the amount extracted from the heated zone during the test was 1000 pounds (4690 - 3690 pounds), resulting in an enhancement factor for the entire course of the test to be 61%. Likewise, consideration of only the period after the temperature front arrived at the extraction vents results in an enhancement factor of nearly 500% (456 pounds removed, 77 pounds expected) from the heated zone. Thus, if a temperature rise similar to that achieved during this test could have been applied over the entire site for long-term operation, it is possible that the cleanup could have been significantly accelerated. Given the measured temperatures and extraction rates, a cleanup period perhaps as short as one-sixth the time required for unheated soil treatment would be necessary for a well-designed and well-operated heated system.

Despite the apparent success of heating enhancement in this test, the results do not conclusively prove the universal value of heat injection for optimization of venting system operation. This is due to several shortcomings of the test and to the fact that the results of this test may not be applicable to systems with different characteristics. The shortcomings of this test entailed limitations of heat input to the soil and distribution of the heat in the soil. Although 650 scfm (0.307 standard meters<sup>3</sup>/second) of gas at or above 600 to 700° F (316 to 371° C) was available at the stack, only about 95 scfm (0.045 standard m<sup>3</sup>/second) at about 210° F (99° C) was delivered at the inlet vent, due to limited vacuum at the vent and heat losses in the 350 feet (107 meters) of piping. With the limited heat input, only a modest but measurable and effective soil temperature increase was induced. Certainly, large improvements could be made using forced injection with a high temperature fan and increased insulation and/or a shorter piping run. More important in uncertainty for extrapolation is the fact that the heat was obviously not evenly distributed in the soil because of the flow geometry.

Upon consideration of these test results, one could conceive of test designs that would allow for greater heated air flow more uniformly distributed. Two such examples are shown in Figure 110. The first shows a ring of inlet vents (either forced or passive) surrounding an extraction vent. With a large number of inlet vents and a surface barrier, a nearly uniform radial flow distribution could be achieved. This design is attractive in that a balance may be achieved between the tendencies for higher temperatures and lower flow rates in outer zones, and lower temperatures (due to conductive heat losses) but higher flow rates near the extraction vent. The other design, more suitable for larger sites, is based upon an attempt to develop one-dimensional linear flow between lines of inlet and extraction vents. The flow patterns would simplify the monitoring of progress of temperature and concentration fronts and would be much more amenable to modeling.

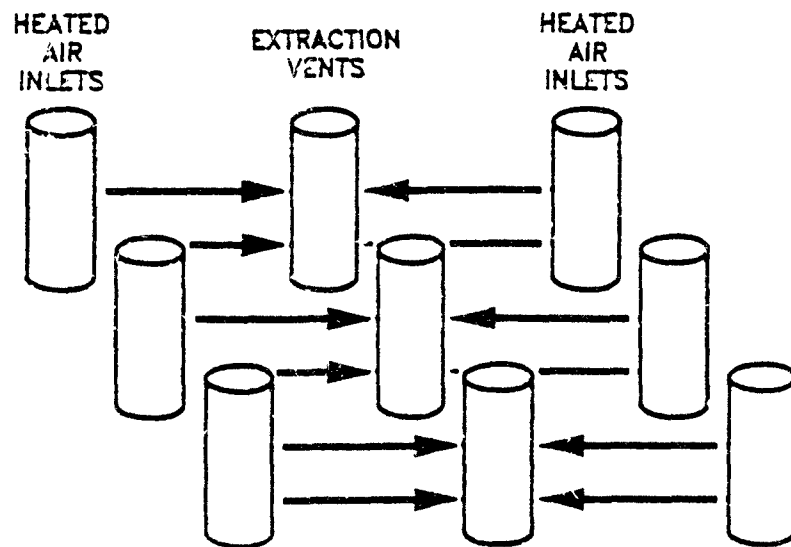
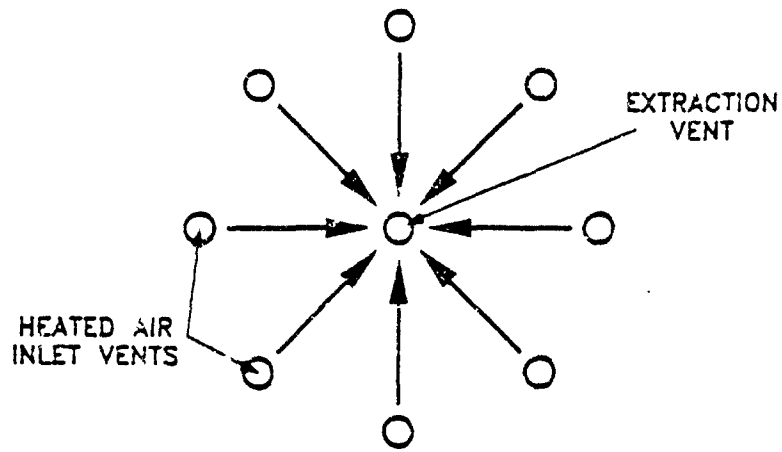


Figure 110. Possible Vent Configurations for Future Heat Injection Tests.

Future tests should also address the impact of heated air injection upon bioactivity. One may be concerned that elevated soil temperatures may harm bioorganisms in the soil. However, two points may be made upon consideration of the results of this test: (1) the temperatures achieved in this test were shown to have the potential for significant increases in removal rate by volatilization, while they were certainly not in the range of harm to most bioorganisms except in the direct vicinity of the inlet vent (in fact, bioactivity may have been increased in much of the heated zone due to the temperature increase); and (2) temperatures high enough to adversely affect bioactivity are also high enough to significantly increase the vapor pressures of contaminants for which biodegradation may be the major means of removal in an unheated case. As was noted earlier, monitoring of bioactivity by measurement of carbon dioxide generation was not possible during this test because of the elevated carbon dioxide levels in the stack gas. One possible means to avoid this complication would be to transfer the stack gas heat to an injection stream of atmospheric air using a heat exchanger.

Despite the shortcomings of this test, some rough estimates of the economics of heat injection at this site may be made. In these estimates, an equilibrium removal model was used to provide an estimate of approximately 1000 liters of air per gram of initial spill material necessary for 80 percent removal by volatilization of the weathered JP-4 at 55°F (12.8°C), or  $2.85 \times 10^9$  scf ( $8.07 \times 10^7$  standard  $m^3$ ) of air would be required (see Volume II). Thus, at an extraction flow rate of 1000 scfm (0.47 standard  $m^3$ /second), 66 months would be required for removal by volatilization in the absence of heat injection. It is with this base case that the heat injection cases are compared. Comparison of the cases would include operating costs and any additional capital cost for the heat injection system components. The piping and stainless steel vents for this demonstration were estimated to cost about \$40,000. For application to the entire site possibly all five central vents or the vents on the fringes could be installed as heat injection vents. It would be preferable to use the latter strategy, since contaminants will be driven away from the heat inlet points. A conservative estimate of additional capital cost for the heat injection system is \$50,000. Operating cost rates would be common to each case, with or without heat injection, with a blower cost of \$1100/month. An average catalytic oxidation cost of \$1900/month was assumed.

Four cases of heat injection corresponding to ranges of removal enhancement deduced from this test are compared with the base case as shown in Table 19. The estimated cost of remediation in the absence of heat injection is \$740,000 to \$1,000,000 (see Section V.J). It is projected that a removal enhancement of approximately 33 percent would be necessary for cost-recovery of the heat injection system. The first case assumes that the approximately 9 percent removal enhancement obtained during this test would be applied to the entire site for the complete remediation. At this rate, a considerable cost is projected for a 10 percent faster clean-up time. The intermediate value of 70 percent, which may be considered a reasonable estimate of long-term removal enhancement, results in significant savings of both time and cost. As would be expected, the optimistic removal enhancement value of 500 percent would yield remarkable savings.

The calculations of Table 19 show that heat injection would be likely to provide savings at the Hill AFB site if reasonable removal enhancement (greater than 33 percent) were achieved. The results of this study indicate that during long-term operation in venting configurations such as those discussed above this would certainly be achieved. Savings would be greater if the site were less permeable (increasing blower costs) or if emissions control were more costly. Certainly, heat enhancement would be much less attractive if emissions control were not required.

Table 19. ECONOMIC COMPARISON OF HEAT INJECTION CASES

	REMOVAL ENHANCEMENT				
	0 Percent	9 Percent	33 Percent	70 Percent	500 Percent
Air needed	$2.85 \times 10^9 \text{ ft}^3$	$2.61 \times 10^9 \text{ ft}^3$	$2.14 \times 10^9 \text{ ft}^3$	$1.68 \times 10^9 \text{ ft}^3$	$4.75 \times 10^8 \text{ ft}^3$
Time at 1000 scfm	66 months	60.5 months	49.6 months	38.8 months	11 months
Additional capital	0	\$50,000	\$50,000	\$50,000	\$50,000
Operating Cost at 1000 scfm	\$3,000/month	\$3,000/month	\$3,000/month	\$3,000/month	\$3,000/month
Total operating & additional capital	\$198,000	\$232,000	\$199,000	\$166,000	\$83,000
Savings due to heating	\$0	- \$34,000	- \$1,000	\$32,000	\$115,000

### 5. Conclusions of Heat Injection Test

This field test has indicated the feasibility of the enhancement of soil venting through heating with the stack gas of a catalytic oxidation emissions control device. Despite the shortcomings of the test, a measurable enhancement of removal due to heating was detected. Results suggest that a system designed with a uniform flow field for more even heating could remediate a site several times faster than an unheated case.

In general the concept of heat injection appears attractive when waste heat is readily available. Heat enhancement will become more economical for systems with higher operating costs, such as sites with soils of low air permeability or costly emissions control. Problems of poor air flow and heat distribution may extend the time required for cleanup and decrease the economical advantage.

Further work in this area, using improved field demonstration systems as described above and complemented with heat and contaminant transport modeling, is urged. Such work would be valuable to further illustrate the advantages of the technique, to define ranges of site variables for which the technique is applicable, and to provide practitioners with a means of estimating soil venting system performance with heating.

## I. EMISSIONS CONTROL BY CATALYTIC OXIDATION

The State of Utah Air Conservation Committee required that an emissions control device be installed to treat the gas extracted from the soil during the full-scale demonstration. An economic analysis indicated that the large contaminant volume and the attractiveness of final destruction capability in an emissions control unit would make catalytic oxidation preferable to carbon adsorption. The two pilot-scale catalytic oxidizers used differed in their catalyst bed designs. The two were (1) a fluidized bed, and (2) a fixed bed. A 500-cfm fluidized-bed oxidation unit was rented from ARI International, and a 1000 cfm fixed-bed oxidation unit was rented from Engelhard, Inc.

Fluidized-bed catalyst oxidizers contain granular particles of catalyst usually comprised of non-precious metal species. The fluidized bed provides a nearly even temperature distribution throughout the bed, allowing high levels of contaminant to be destroyed without thermal damage to the catalyst. The fluid action of the bed also counteracts fouling of the catalyst due to the abrasive forces on the outer catalyst surfaces. For this same reason, catalyst will gradually be lost and must be replaced (thus the preference for nonprecious metal catalysts).

Fixed-bed catalytic oxidizers contain catalyst in a stationary form, such as precious metals deposited on a honeycomb ceramic substrate. Because of the unitary nature of the catalyst, a temperature gradient will be induced along the bed as contaminants are oxidized, thus limiting the contaminant levels which may be fed without thermal damage to the unit. Fixed-bed catalysts are susceptible to fouling by species in the gas stream such as sulfur compounds, as noted in the results of the AFESC-sponsored demonstration of Air Stripping with Emissions Control (Reference 31). Because little catalyst loss is encountered, the added effectiveness of precious metal catalytic species may be employed.

### 1. Operation

The fluidized-bed oxidizer was operated for eight months, between December 1988 and August 1989. The fixed-bed oxidizer was operated for six months, from April 1989 to October 1989. Both units performed very well from an operational standpoint, even in adverse conditions such as harsh winter weather. The control systems were well designed, allowing relatively trouble-free startup and shutdown and smooth, unmanned operation. Little maintenance was required. The bearings on the process fans required weekly lubrication, and, less frequently, the filter on the combustion air blower of the fluidized-bed oxidizer was cleaned of snow or sand. One hundred pounds (45.4 kg) of catalyst were added to the initial 150-pound (68.0-kg) charge in the fluidized-bed oxidizer over the course of the demonstration to maintain catalyst bed depth.

A problem with operation of both oxidizers was windblown sand which caused binding of the control motor and linkages for the preheater propane control valves. Increased weatherproofing of these components would improve operability. Because the fluidized-bed unit was under positive pressure between the preheater and catalyst bed, small amounts of gas containing a brown condensible viscous material (assumed to be the products of incomplete combustion) escaped through small leaks around the unit. It was necessary to patch these leaks. A unit under negative pressure would avoid this problem, but would have to be designed to allow for solids entrainment and high temperature gas.

## 2. Conversion Results

### a. Fluidized-Bed Oxidizer

During the operation of the fluidized-bed oxidizer, 15 sets of inlet and outlet samples were analyzed for total organics allowing the calculation of the destruction efficiency for the oxidizer, which varied from 78.2 to 99.4 percent, with an average of 88.8 percent. A summary of the results is shown in Table 20 for the fluidized-bed oxidizer.

TABLE 20. SUMMARY OF RESULTS FOR FLUIDIZED-BED OXIDIZER

DATE	TEMPERATURE (F)		TOTAL ORGANICS ( $\mu\text{g/liter}$ )		DESTRUCTION EFFICIENCY (Percent)
	IN	OUT	IN	OUT	
02/01/89	675	1052	2336	152.5	93.5
02/07/89	650	1056	18339	101.9	99.4
03/20/89	650	1056	17980	273.5	98.5
03/22/89	600	1045	17380	255.6	98.5
04/29/89	625	848	7675	1006.0	86.9
05/14/89	625	847	7294	478.0	93.4
05/26/89	625	869	1639	292.3	82.2
06/13/89	700	918	5163	176.0	96.6
06/22/89	700	883	4658	508.5	89.1
06/29/89	650	803	5563	890.7	84.0
07/07/89	650	743	3802	828.4	78.2
07/13/89	650	752	3196	590.4	81.5
07/25/89	650	688	2289	462.9	79.8
07/23/89	650	694	1573	267.4	83.0
08/11/89	650	665	2015	241.5	88.0

### b. Fixed-Bed Oxidizer

During the operation of the fixed-bed oxidizer, 14 sets of inlet and outlet samples were analyzed for total organics. The fixed-bed oxidizer was significantly more efficient, ranging from 92.6 to 99.7 percent destruction, with an average of 97.3 percent for 14 sets of samples. Table 21 summarizes the results for the fixed-bed oxidizer.

TABLE 21. SUMMARY OF RESULTS FOR FIXED-BED OXIDIZER

DATE	TEMPERATURE (F)		TOTAL ORGANICS ( $\mu\text{g/liter}$ )		DESTRUCTION EFFICIENCY (%)
	IN	OUT	IN	OUT	
04/29/89	525	860	7675	99.3	98.7
05/14/89	525	800	7294	123.7	98.3
05/26/89	525	830	1639	60.7	96.3
06/13/89	550	940	5163	91.6	98.2
06/22/89	550	920	4658	161.2	96.5
06/29/89	520	890	5563	163.7	97.1
07/13/89	470	800	3196	236.2	92.6
07/25/89	495	760	2289	117.0	94.9
07/28/89	510	745	1573	41.4	97.4
08/11/89	480	700	2015	48.0	97.6
08/18/89	625	810	1460	26.1	98.2
08/25/89	620	810	1081	23.1	97.9
09/11/89	600	750	1073	17.5	98.4
09/15/89	625	760	622	1.6	99.7

### c. Discussion of Conversion Results

Significant differences were observed between the oxidizers in terms of hydrocarbon destruction efficiency. These differences were mainly due to the mode of operation, rather than to design details.



The fixed-bed unit provided consistent performance throughout the venting test. The destruction efficiency dropped to less than 95 percent only when the inlet temperature was reduced to less than 500°F (260°C). The destruction efficiency of the fixed-bed unit increased slightly as the temperature of the gas entering the unit increased (Figure 111), but the efficiency seemingly did not depend on the outlet temperature, the inlet organic concentration, or the length of time the unit operated.

The destruction efficiency of the fluidized-bed oxidizer was sensitive to the operating conditions. The efficiency was positively correlated with the outlet temperature (Figure 112) and the inlet organic concentration (Figure 113), but did not depend on the inlet temperature. The destruction efficiency of the fluidized-bed unit decreased during the eight months that the oxidizer was operated. The reason for this decrease in conversion with operating time is the mode of operation. The catalyst bed inlet temperature was held nearly constant in the range of 625 to 700°F (329 to 371°C), maintaining a reasonable temperature rise compared to inlet concentration, but allowing the outlet temperature to drop as inlet hydrocarbon concentration decreased. Although this mode of operation is useful for illustrating the variation of conversion efficiency with outlet temperature, it does not maintain optimal destruction efficiency. A more satisfactory mode of operation would be to periodically adjust the catalyst bed inlet temperature set point to maintain outlet temperature levels which ensure desired destruction efficiencies, in this case in the range of 1000 to 1050°F (538 to 566°C). Given the data collected, there is no reason to conclude that the fluidized-bed unit would not have maintained high conversion if operated in this manner.

There also appears to be a difference between the oxidizers in terms of the composition of constituents in the off gas. As shown in Figure 114, which depicts the results of nine paired samplings of inlet and outlet gas concentrations of both units, the fluidized-bed unit appeared to release a wider boiling point range of compounds, both at the low and high boiling point range of interest, than the fixed-bed unit. The fixed-bed unit demonstrated the ability to destroy C7 and lower compounds.

### 3. Propane Consumption

An estimate of the propane usage by each unit was made based on the amount of propane required to refill the supply tanks. Average propane usage for each oxidizer is listed in Table 22. Average daily propane costs in the table are based on a purchase price of \$0.429 per gallon.

Table 22 indicates that the fluidized-bed unit was more expensive to operate on a gas volume treated basis. These values represent average values over the course of the demonstration. It is expected that average propane consumption, particularly for the fluidized-bed unit, would increase during extended operation at optimal destruction efficiencies.

### 4. Conclusions of Emissions Control Monitoring

*In situ* soil venting applications provide a challenging vapor stream for treatment by an emissions control device since the gases are normally of high relative humidity and range over several orders of magnitude in contaminant concentration over the course of operation. Catalytic oxidation becomes a very attractive alternative for soil venting emissions control since heating requirements are much lower than thermal oxidation and the humidity, manpower, and final disposal problems of carbon adsorption are avoided.

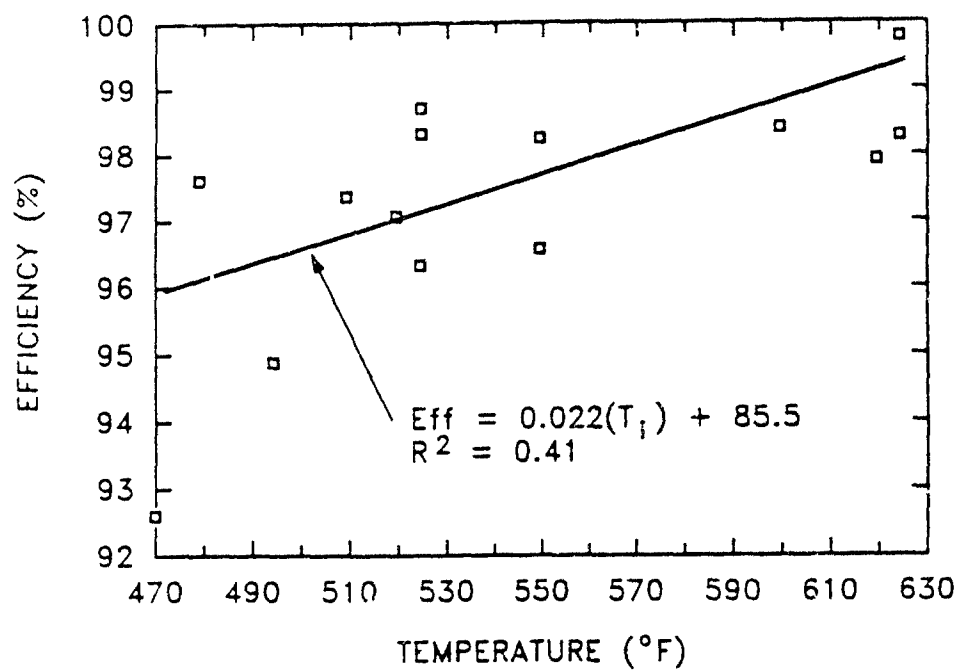


Figure 111. Destruction Efficiency of Fixed-Bed Catalytic Oxidizer as a Function of Inlet Temperature.

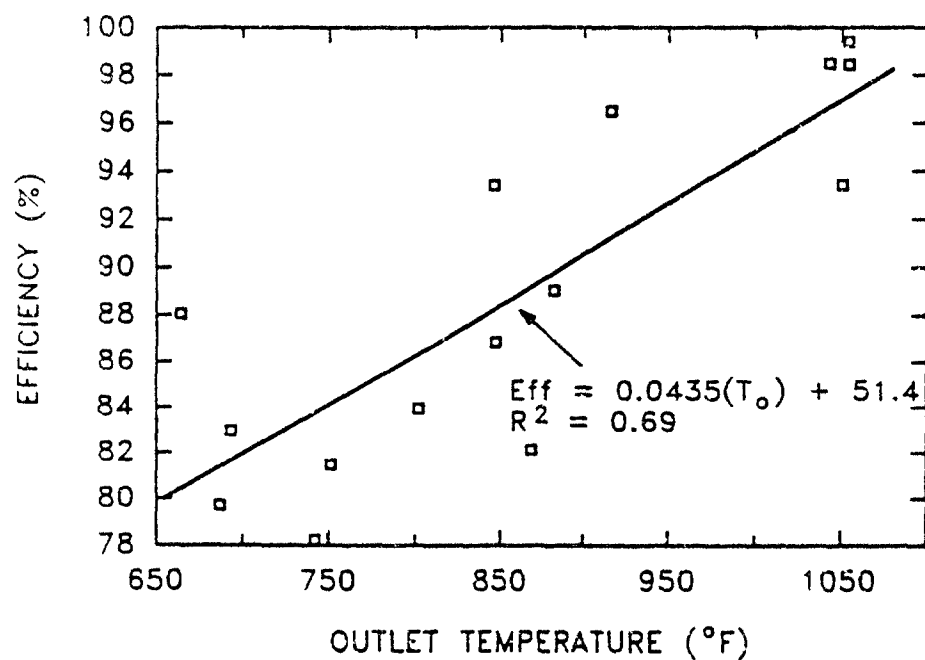


Figure 112. Destruction Efficiency of Fluidized-Bed Catalytic Oxidizer as a Function of Outlet Temperature.

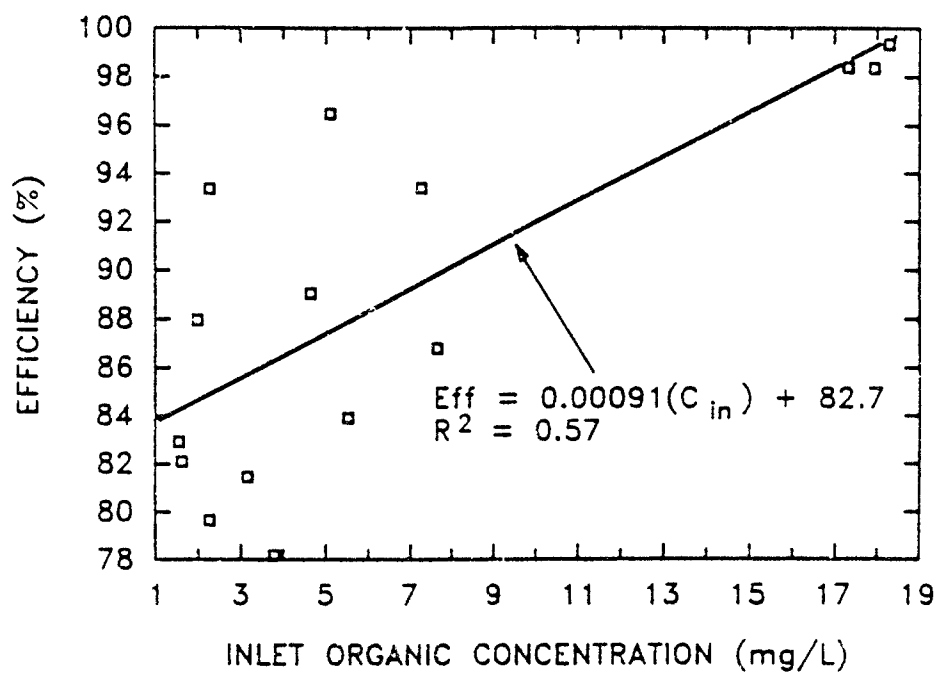


Figure 113. Destruction Efficiency of Fluidized-Bed Catalytic Oxidizer as a Function of Inlet Organic Concentration.

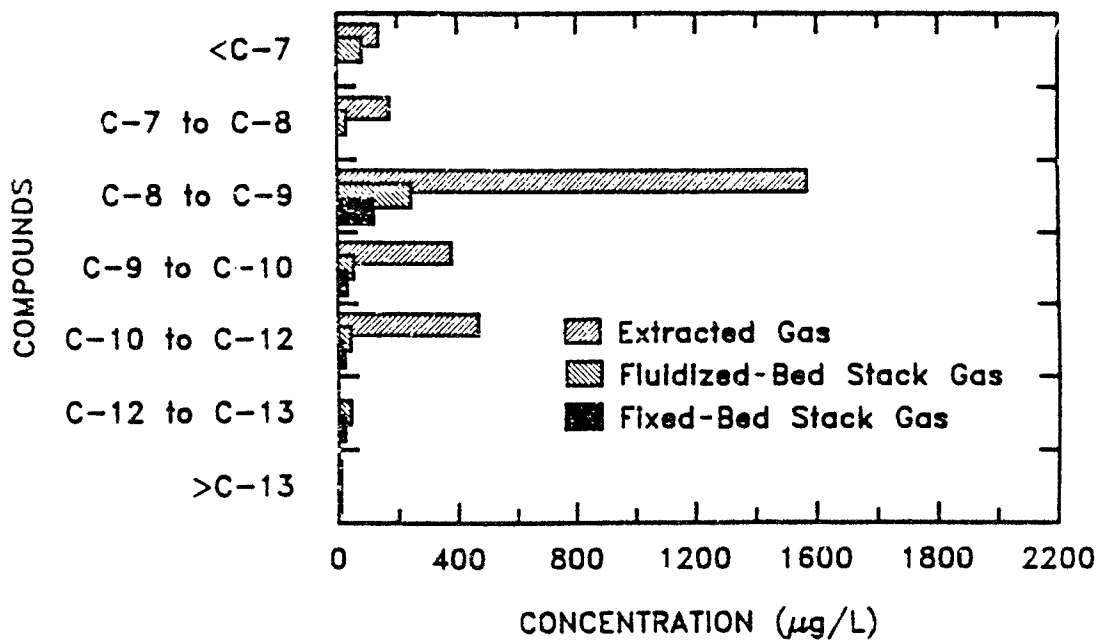


Figure 114. Inlet and Outlet Gas Concentration and Composition for Oxidizers (22 June 1989).

TABLE 22. AVERAGE PROPANE USAGE FOR CATALYTIC OXIDIZERS

OXIDIZER(S) USED	AVERAGE PROPANE USED (gallon/day)	AVERAGE COST (\$/day)	AVERAGE PROPANE USAGE (gal/10 <sup>6</sup> ft <sup>3</sup> AIR TREATED)	AVERAGE COST (\$/10 <sup>6</sup> ft <sup>3</sup> AIR TREATED)
Fluidized-bed	50	21.5	69.4	29.8
Fixed-bed	80	34.3	55.6	23.8
Both units	130	55.8	60.2	25.8

This application successfully demonstrated the use of catalytic oxidation as an emissions control option for soil venting. In this demonstration, the contaminant concentrations during the early phases of venting were above the upper concentration limit of the oxidation (due to catalyst bed temperature rise) noted by Johnson et al. (Reference 32). By diluting the gas stream with air to reduce the concentration to 20 percent LEL or below at the inlet, operation of the unit was possible. Although dilution limits the removal rate during the initial operation, it avoids the logistics of switching emissions control devices. Economics for application of the oxidizers to the lower concentration periods might have been improved through heat recovery. Heat injection as described in section V.H. also provides promise for improving the economics of the process.

Both catalytic units tested, of fixed-bed and fluidized-bed design, performed satisfactorily. The units operated automatically with little attention or maintenance required. The ease of use, along with single step contaminant destruction capability, increases the attractiveness of this emissions control option.

Although the designs tested both performed well, there are particular applications in which each would have a decided advantage. Fixed-bed units may include specially formulated catalysts containing precious metals and, therefore, may in many cases be operated at lower temperatures than fluidized-bed units utilizing nonprecious metal species. As seen in this demonstration, the fixed-bed catalytic unit could be operated at much lower inlet temperatures than the fluidized-bed unit for adequate destruction, resulting in lower preheater fuel costs. In larger systems, the fuel cost difference could be decreased through heat recovery. Fixed-bed catalytic oxidizers are less flexible due to their susceptibility to fouling or poisoning. Fluidized-bed systems are thus more applicable to situations including poisoning species such as sulfur or contaminant streams containing chlorinated organics. A determination of gas stream components should be made before specification of catalytic oxidizer type for environmental applications.

## J. EFFECTIVENESS OF SITE TREATMENT

### 1. Post-Venting Soil Analyses

Following completion of venting operations, soil samples were collected from the vertical vent area and from the pile to assess the effectiveness of venting in removing hydrocarbons from these areas. Post-venting samples in the lateral venting zones were not taken due to the presence of the concrete tank enclosure. For both systems, post-venting samples were collected at locations and at depth intervals which were as close spatially as possible to the pre-venting samples (generally within 5 feet laterally and 1 foot vertically). The post-venting and pre-venting samples thus comprise matched pairs which may be compared to evaluate the hydrocarbon removal efficiency. Post-venting borings were designated "A" to distinguish them from pre-venting borings.

#### a. Total Hydrocarbons

##### (1) Vertical Vent System

Borings drilled in the vertical vent area following venting are shown in Figure 115. Borings were drilled adjacent to vent borings which contained at least one pre-venting sample of greater than 100 mg/kg total hydrocarbons. These included vents having labels V2, V3, V4, V6, V7, V8, V9, V10, V11, V14, V15, and E. Additional borings were installed (1) adjacent to V4 (4B) and V11 (11B), to provide indications of replicability between paired samples on a 10-foot scale; and (2) equidistant between V4 and V11 (4C) to assess venting effectiveness at a boundary "node" between vents. Because no significant contamination was found during pre-venting sampling in borings V1, V5, V12, or V13, no post-venting borings were drilled at those locations. Four samples were collected in the upper 5 feet of soil by hand auger (at locations V4A and V11A) to avoid encountering possible subsurface obstructions.

Analyses of post-venting samples collected from the vertical vented area are summarized in Table 1 of Appendix G. Total hydrocarbon concentrations ranged from nondetectable (<20 mg/kg) to a maximum of 424 mg/kg. The analyzed hydrocarbon levels were considerably lower than in the pre-venting samples; only nine analyses exceeded 100 mg/kg, and four of these were from boring V3A. The mean of two trip blanks was 42 mg/kg; only 29 of the 110 samples equaled or exceeded this value. Replicability was high: in only one of the 9 pairs of field replicates did the 2 values differ by greater than 12 mg/kg. Comparison of analyses for borehole pairs 4A/4B and 11A/11B show excellent agreement between "replicate" boreholes: means of hydrocarbon analyses for 4A and 4B were 32 mg/kg (SE 8) and 32 mg/kg (SE 5), respectively, while for 11A and 11B means were 37 mg/kg (SE 10) and 39 mg/kg (SE 5).

##### (2) Pile

Pile post-venting samples were collected from six borings (Figure 12) in the same manner as for the vertical vents, i. e., from borings and depth intervals adjacent to those which had contained greater than 100 mg/kg in pre-venting samples. A total of 13 samples were analyzed from six borings, all in the western half of the pile. Of the samples analyzed, only one exceeded 100 mg/kg in hydrocarbon concentration.

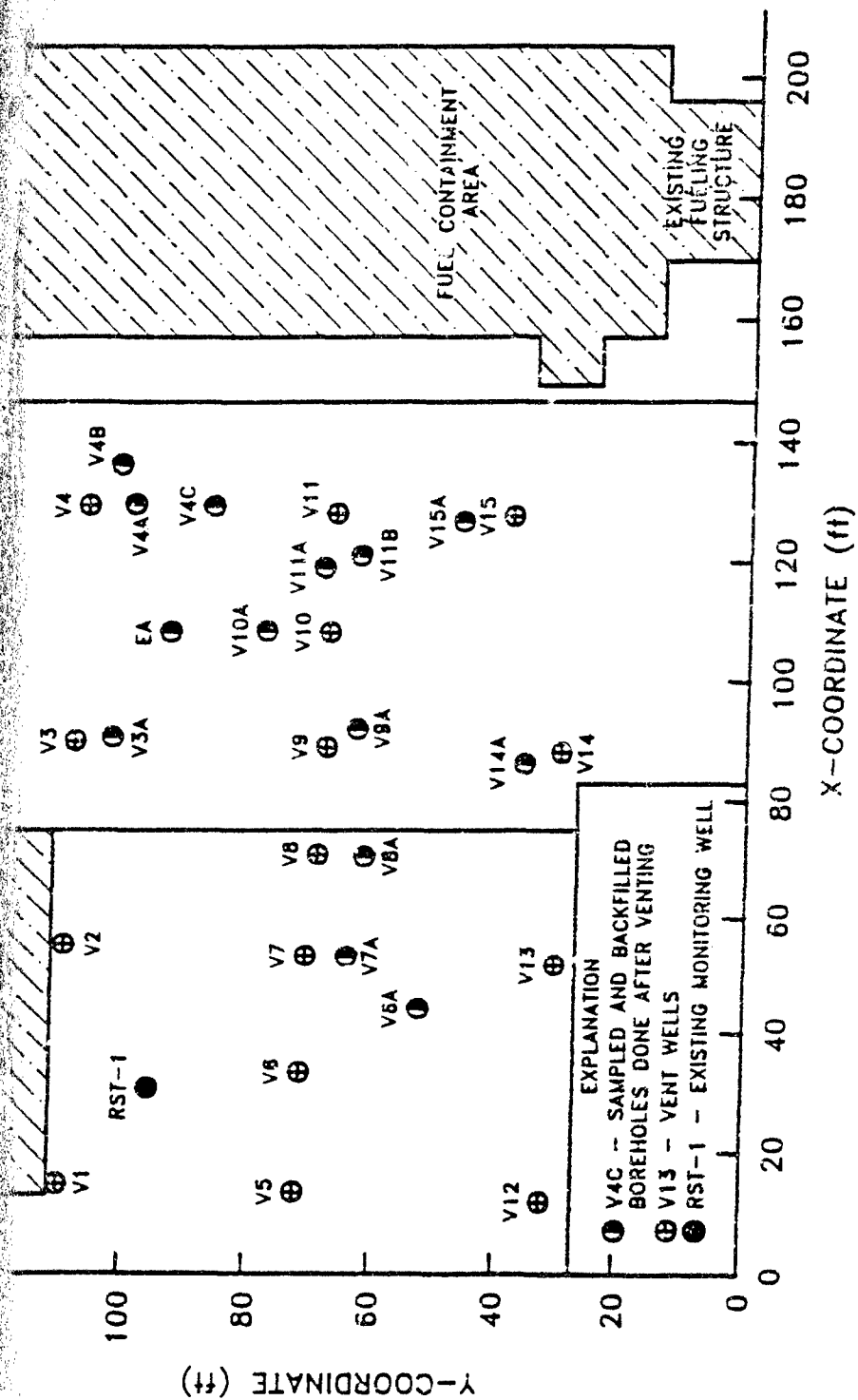


Figure 115. Location of Borings (Identified by the Designation "V\_A," V\_B," or "V\_C") Installed for Post-Venting Characterization in the Vertical Vent Area.

### **b. Moisture Content**

Moisture contents of the post-venting soil samples are summarized in Table 3 of Appendix G. Moisture contents of the pile varied from 2.4 percent to 8.8 percent, or approximately the same as pre-venting samples. Most samples from the vertical vent system borings were in the same range, with values reflecting near-saturated conditions (23 to 30 percent) above clay layers as in the pre-venting samples. Moisture contents reflected the results of neutron access tube studies which suggested that little change in moisture content of the vented soil occurred except in the upper 8 to 10 feet.

### **c. Benzene, Toluene, and Xylene (BTX)**

Post-venting samples corresponding to six of the samples which contained relatively high pre-venting levels of BTX were analyzed for BTX. In addition, the four post-venting samples which contained the highest levels of total hydrocarbons (Nos. 4664, 4667, 4686, and 4712 in Table 1 of Appendix G) were analyzed for BTX. These samples and corresponding depth intervals are shown in Table 4 of Appendix G.

No BTX were detected in any of the 10 samples (detection limit: 10 mg/kg). Because these samples were selected to represent those which might be expected to have the highest likelihood of containing BTX, the data strongly suggest that BTX were effectively reduced to nondetectable levels (i. e., <10 mg/kg) by the venting operation.

## **2. Effectiveness of Hydrocarbon Removal**

To assess the effectiveness of venting, the mass of fuel hydrocarbons remaining in the vertical vented zone and the pile were computed for the post-venting sampling campaign. The same grids were used as in determination of pre-venting soil hydrocarbon mass (Section III.C.). For the vertical vent area, only the borings labeled "A" were compared with pre-venting samples.

### **a. Vertical Vent System**

The worksheet for calculation of the hydrocarbon removal efficiency for the vertical vent area is shown in Table 5 of Appendix G. Soil sub-volumes were defined as described in Section III.C.

The total amount of hydrocarbons remaining in the vertical vented zone following venting is calculated to be 2650 pounds (1309 kg). Based on an initial hydrocarbon mass in this area of 30,760 pounds (13,952 kg), the removal efficiency for the vertical vent system is 90.6 percent. For sub-areas which contained measurable hydrocarbons before venting, the effectiveness of hydrocarbon removal varied from 47.6 percent (V15) to 97.5 percent (V10).

A large number of samples contained hydrocarbon at undetectable levels (i. e., <20 mg/kg) in the pre-venting samples. To produce a conservative estimate of hydrocarbon removal in the preceding analysis, the concentration of hydrocarbons in these samples (estimated at one-half the detection limit, or 10 mg/kg) was assumed to remain unchanged during venting. The mass of hydrocarbons in sub-volumes associated with these samples thus becomes disproportionately far more significant in calculation of the post-venting residual hydrocarbon mass. This is because high hydrocarbon concentrations, which accounted for the predominant portion of total hydrocarbon mass, are no longer observable in the post-venting sample analyses.

To evaluate the effect of the large volume of soil calculated to contain residual hydrocarbons at an undetectable but nonzero (estimated to be 10 mg/kg) concentration, the effectiveness of removal of hydrocarbons from soil which contained detectable hydrocarbons in pre-venting samples was calculated. A total of 58 sample intervals from 12 borings contained detectable hydrocarbons in the pre-venting sampling. These contribute 29,820 pounds (13,285 kg), or 97 percent, of the total calculated pre-venting hydrocarbon mass [30,760 pounds (13,952 kg)] in the vertical vent zone. The total hydrocarbon mass remaining in these sub-zones following venting is 1560 pounds (708 kg), or only 54 percent of the total [2886 lbs (1309 kg)] calculated to be present when nondetectable values are included. The effectiveness of hydrocarbon removal when nondetectable concentrations are excluded, is thus calculated to be 94.8 percent. This value is considerably higher than the value calculated (90.6 percent) when nondetectable concentrations are included, and probably represents a more accurate measure of the effectiveness of the vertical venting system.

#### **b. Pile**

The residual mass of hydrocarbons in the excavated pile and calculation of the effectiveness of venting were performed in a manner analogous to that of the vertical vent system (see Table 6 of Appendix C). The total calculated post-venting hydrocarbon mass is 143 pounds (65 kg). Based on an initial hydrocarbon mass of 2190 pounds (994 kg), the effectiveness of hydrocarbon removal is 93.4 percent.

As was true for the vertical vent zone, the effect of nondetectable hydrocarbon concentrations is also significant for the pile. Soil subvolumes associated with nondetectable hydrocarbon concentrations comprise one-half of the pre-venting pile analyses (i. e., all samples from borings P7-P12). These subvolumes add a calculated hydrocarbon mass of 48 pounds (22 kg) to both pre- and post-venting hydrocarbon inventories. When this mass is removed from each, the pre- and post-venting hydrocarbon masses in the pile are calculated to be 2140 pounds (972 kg) and 95 pounds (43 kg), respectively. The calculated hydrocarbon removal effectiveness calculated on the basis of these figures is 95.5 percent. This figure is essentially identical to the vertical vent zone removal efficiency (excluding nondetectable hydrocarbon analyses) of 94.8 percent.

### **3. Factors Affecting Hydrocarbon Removal**

#### **a. Depth**

The screens employed in the vertical vent system extended from 10 feet to 50 feet (3.0 to 15.2 meters) BLS. To determine whether the soil in the upper 10 feet (3.0 meters) was vented as effectively as the deeper soil, subzones in the 0- to 10-foot (0- to 3.0-meter) depth range whose pre-venting sample analyses contained measurable hydrocarbons were evaluated. A total of 13 subzones from seven subareas met these criteria. The efficiencies of hydrocarbon removal from these subzones are summarized in Table 23. Removals ranged from 83.2 percent to 98.9 percent; the mean removal was 96.3 percent. This value is higher than the removals calculated both including and excluding nondetectable concentrations for the entire vertical vent zone (90.6 percent and 94.8 percent, respectively). Results therefore demonstrate that hydrocarbon removal in the upper 10 feet (3.0 meters) of soil, above the tops of the vent screens, was at least as effective as hydrocarbon removal in the deeper zone.



TABLE 23. PRE- VERSUS POST-VENTING HYDROCARBON MASS; UPPER 10 FEET OF SOIL ONLY

VENT NO.	HC MASS (mg/kg)		REMOVAL EFF. (Percent)
	PRE-VENTING	POST-VENTING	
V2	385.44	30.81	92.01
V4	661.63	25.54	96.14
V7	203.31	17.62	91.34
V8	44.64	7.50	83.19
V9	626.87	8.30	98.68
V10	1282.13	13.72	98.93
V11	349.03	27.50	92.12
TOTAL	3553.09	131.00	96.31

b. Presence of Clay

To assess the effect of clay layers on hydrocarbon removal, sub-zones defined by biased samples (i. e., those collected at the interfaces between sand and underlying clay), which contained measurable pre-venting hydrocarbons, were compared for pre- and post-venting samples. A total of seven subzones from six borings were identified; results are shown in Table 24. The overall hydrocarbon removal effectiveness in the seven sub-zones is calculated to be 97.5 percent, or substantially higher than the vertical vent zone considered as a whole.

Because post-venting samples were collected at the same depth interval as pre-venting samples, but not by examination of a continuous core (the post-venting boreholes were not continuously logged), it is possible that the post-venting samples may not represent the same position relative to the sand-clay interface as do the pre-venting samples. Of the seven samples in Table 25, only two (samples 4672 and 4679 in Table 1 of Appendix G) were observed to consist unambiguously of clay in subsamples dried for moisture determination, while a third (No. 4667) was composed largely of clay. Perhaps significantly, these three samples had the highest hydrocarbon concentrations of the seven depth intervals shown in Table 25. The hydrocarbon removal effectiveness of the subzones corresponding to these three samples, however, are all greater than 94.4 percent, which suggests that hydrocarbon removal from the clay layers was as effective as from bulk sand.

Additional qualitative evidence for the effectiveness of hydrocarbon removal from clay layers in the vertical vent zone comes from observation of the dried samples for moisture determination. Post-venting samples visually categorized as "clay," in addition to those listed above, included samples numbered 4632, 4640, 4648, 4651, 4652, and 4672 in Table 1 of Appendix G.

TABLE 24. PRE- VERSUS POST-VENTING HYDROCARBON MASS: BIASED SAMPLES ONLY

VENT NO.	DEPTH (feet)	PRE-VENTING (BIASED)	POST-VENTING (BIASED)	REMOVAL EFF. (Percent)
V3	38	146.28	8.19	94.40
V4	18	107.46	1.07	99.00
V8	27.5	11.21	0.43	96.20
V8	47	97.24	0.73	99.24
V10	39	90.09	1.95	97.84
V11	36	286.55	3.61	98.74
V15	10.5	1.82	1.83	-0.44
	TOTAL	740.99	18.16	97.55

Concentrations of hydrocarbons did not exceed 100 mg/kg in any of these samples. Of the nine samples in Table 1 of Appendix G which did exceed 100 mg/kg, all but 4667 (identified above as a sand-clay mixture) were identified visually as "sand." The results, therefore, support the conclusion that hydrocarbons were removed from clay and near-clay zones with essentially the same degree of effectiveness as from the bulk sand.

#### c. Moisture

The post-venting samples identified visually as "clay" all had moisture contents greater than 23 percent. Because of the strong apparent correlation between clay content and moisture, it would be difficult to determine which is the controlling variable if in fact hydrocarbon removal were correlated with moisture content.

To assess the effect of moisture, moisture content and hydrocarbon content for the 155 post-venting samples from both vertical vent wells and pile for which both analyses were run were regressed. The results (Figure 116) demonstrate no significant relationship between the two variables ( $R^2=0.013$ ). Moisture seems therefore to have had little effect on hydrocarbon removal in the vertical vent area.

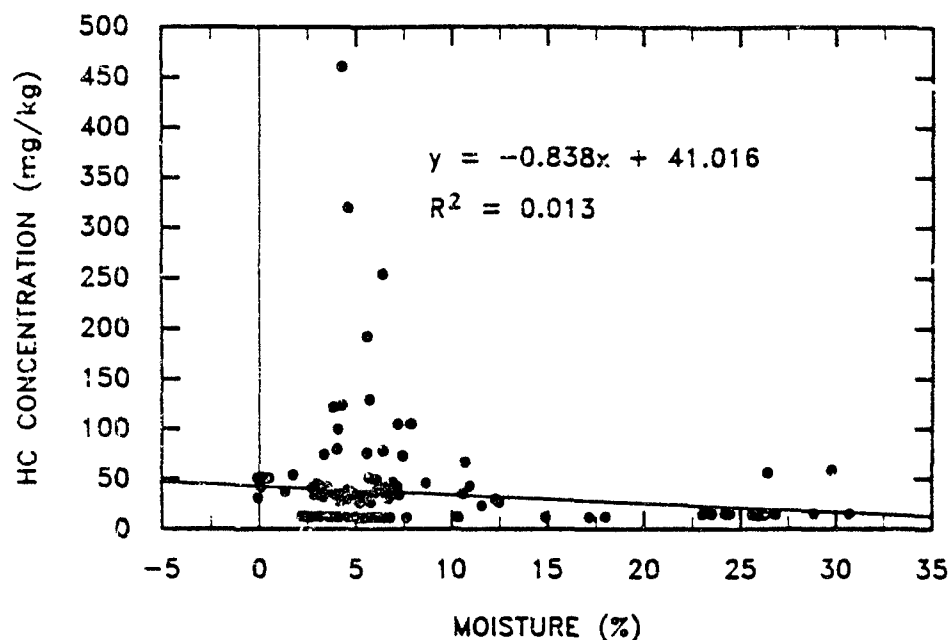


Figure 116. Regression of Measured Hydrocarbon Content (mg/kg) Against Moisture Content for the Suite of Post-Venting Soil Samples from Both the Pile and Vertical Vent Area Borings.

#### d. Other Geohydrologic Factors

No effects of other geohydrologic factors are apparent from examination of the post-venting hydrocarbon data. The subzone which consistently showed the least effective removal of hydrocarbons was V3; in addition to a hydrocarbon removal efficiency of only 79.6 percent (82.4 percent with exclusion of hydrocarbon "nondetects"), four of the nine highest post-venting hydrocarbon levels were determined in this sub-zone. All occurred between 23.5 feet and 38 feet (7.2 meters and 11.6 meters) BLS, suggesting the existence of a "dead zone" of minimal air flow. However, examination of the boring log from V3 does not indicate any unusual features: the soil consists of medium- to fine-grained sand, moderate- to well-sorted. A thin clay lens was observed at 38 feet (11.6 meters) BLS, but similar lenses occur in other boreholes; this feature would also not be expected to affect vapor flow 15 feet (4.6 meters) higher in the 23.5- to 25-feet (7.2 to 7.6-meter) interval.

An alternate explanation for the elevated hydrocarbon residues found in V3A may be that hydrocarbon contamination moved into this area from beneath the waste oil tank garden, just to the north from subzone V3. No data are available concerning hydrocarbon levels in the soil beneath this bermed area; however, the different hydrocarbon distributions observed in samples from V3 (Section III) suggest that other spills have occurred in this area. A hydrocarbon reservoir of considerable size may occur beneath this area, and contaminants from beneath the garden may have migrated into the V3 subzone under the influence of the vent air flow.

#### e. Distance from Vents

Because Vents 7, 9, 10, and 11 were operated for longer periods than were the other vents, it might be expected that efficiencies of hydrocarbon removal would be greatest in the subzones which encompass these vents. Conversely, because boring E was located at a node between Vents 3, 4, 9, and 11, which was expected by flow modeling to be an area of reduced air flow during operation in a grid configuration, it might be expected that efficiency of hydrocarbon removal would be minimal in this subzone.

Hydrocarbon removals from V7, V9, V10, and V11 were 68.6 percent, 97.2 percent, 97.5 percent, and 92.2 percent. The overall removal efficiency for these sub-zones was 95.3 percent, which is considerably higher than the 90.6 percent effectiveness of the entire vertical vent system. When only detectable hydrocarbon concentrations are considered, the effectiveness figures are 93.9 percent, 98.4 percent, 98.1 percent, and 96.6 percent, respectively (overall: 97.9 percent); again, higher than the overall vertical vent area effectiveness (94.8 percent). The calculated hydrocarbon removals for boring E with and without inclusion of nondetectable hydrocarbon analyses were 94.4 percent and 95.2 percent, respectively. These values are above the mean removal figures for the vertical system. The reason may be that because most of the venting operation was conducted through vents V9, V10, and V11; boring E was located at a pressure node only during a small portion of the total operation. Because of a malfunction in the pressure monitoring point installed in boring E it is not possible to determine pressure gradients, nor to demonstrate air flows, through this soil volume. However, because of the proximity of boring E to V9, V10, and V11 and measured pressure decreases in monitoring points considerably farther from these vents, it is likely that air flows through the boring E subzone were sufficient to account for the high hydrocarbon removal effectiveness.

#### 4. Comparison of Total Hydrocarbon Removal Determined from Soil and Off-Gas Measurements

The total quantity of hydrocarbons removed from the soil was considered to be no greater than the sum of the hydrocarbons removed from each of the three zones (Table 25).

TABLE 25. CALCULATION OF HYDROCARBON REMOVAL  
BASED ON SOIL SAMPLES

	PRE-VENTING	POST-VENTING	DIFFERENCE
Vertical vents	13,952 kg	708 kg	31,244 kg
Beneath excavation	3,574	0*	3,574
Pile	972	43	929
TOTAL			17,747 kg

\*Assuming complete hydrocarbon removal.

The calculated value for total hydrocarbon removal from the vented zones was thus 39,132 pounds (17,747 kg). In contrast, the total mass of hydrocarbons removed in the vented air stream during the entire project was 105,000 pounds (47,619 kg). The quantity of hydrocarbons removed was thus 268 percent of the initial calculated hydrocarbon mass.

Several hypotheses were proposed to explain the difference between these two hydrocarbon mass estimates. Each is considered below, with an assessment of the supporting or refuting evidence, and an estimate of the most likely magnitude of effect.

a. Soil analyses systematically underestimated the true soil hydrocarbon concentrations.

Pre-venting analyses of soil samples collected beneath the excavated tanks undoubtedly underestimated the true values due to volatilization loss of the lighter components during sample processing. The loss was estimated at 25 percent (Section III.B.3). Because the subexcavation hydrocarbon mass was 25 percent of the total, the effect of sampling error in this zone is to underestimate the total pre-venting mass by 6 percent.

The mean mass recovery of JP-4 "spikes" added to 20 samples was 106 percent (SE = 7 percent). There thus appears to be no evidence for systematic underestimation of hydrocarbons in the soil samples apart from the sample set described above.

b. The off-gas hydrocarbon concentration was systematically overestimated.

During the initial stages of venting the total hydrocarbon concentration measured continuously with the Total Hydrocarbon Analyses (THA) agreed closely with values measured by gas chromatography in grab samples. However, after total hydrocarbon levels declined below 1000 ppmv (i. e., after approximately  $30 \times 10^6$  ft<sup>3</sup> of gas had been extracted), concentrations measured with the THA exceeded grab sample analyses by a mean factor of 1.6. If the total hydrocarbon concentrations measured by gas chromatography are assumed to be accurate, the total removed would be 97,000 pounds (44,000 kg), rather than 105,000 pounds (47,600 kg), or a reduction of 8 percent. However, sorption of hydrocarbons onto the metal walls of the grab sample collection vessels would be expected to be most noticeable at low total hydrocarbon concentrations. There are insufficient data to differentiate between the two alternate hypotheses at this time.

c. Off-gas analyses included hydrocarbons not measured in soil analyses.

The on-line total hydrocarbon analysis included all hydrocarbons, including methane, ethane, and other low-molecular-weight compounds. The soil analytical procedure, in contrast, measured only C<sub>6</sub> and higher-molecular-weight compounds. If the off-gas contained a substantial portion of low-molecular-weight compounds, this might explain the difference between the gas and soil analyses. However, the gas grab sample chromatographic analyses did not show major peaks early in the chromatograms where such compounds would elute; moreover, the chromatographic analyses, which quantified C<sub>7</sub> compounds and above, did not differ substantially from the on-line analyzer results. This does not therefore appear to explain the difference between soil and gas hydrocarbon masses.

- d. Substantial quantities of soil fuel residues were "missed" between sampling intervals during the pre-venting sampling.

In order to account for the discrepancy of 65,868 pounds (29,872 kg), the volume of soil, contaminated at the highest level measured (6400 mg/kg), "missed" would be approximately  $5 \times 10^6 \text{ ft}^3$  (141,600  $\text{m}^3$ ). This corresponds to a volume of 500 feet x 200 feet x 50 feet (152 meters x 61 meters x 15 meters). It seems highly unlikely that a contaminated soil volume of this size could be present in "pockets" within a grid of samples collected at 40 feet x 5 feet (12.2 meter x 1.5 meter) intervals.

- e. The lateral extent of contamination was underestimated.

If in fact the fuel contamination zone were more extensive than assumed, the total mass of fuel initially present would of course be underestimated. In preliminary soil gas surveys, no evidence was found for fuel contamination to the north, west, or south of the site. No data are available concerning possible contamination north or south of the tank excavation, or north of vertical vent V4. If these areas contain as much residual fuel as the adjacent sub-areas, the total initial fuel present could be underestimated by 15 percent to 20 percent. Although the known path of fuel movement during the January 1985 spill did not extend beyond the area defined by the vertical vent field, earlier spills could have contributed to hydrocarbon residues throughout the area (see below).

- f. The vertical extent of contamination was underestimated.

No evidence was found for penetration of fuel deeper than the sampled depth throughout the vertical vent zone. However, contamination was detected in one boring (BH16) at least 4 feet (1.2 meters) into the clay beneath the tank excavation, with no evidence that the lower bound of contamination had been reached. The mean fuel concentration measured in BH16 in the clay, at 27 to 31 feet (8.3 to 9.4 meters), was 600 mg/kg. If the total depth of contamination in the clay layer is assumed, as an upper estimate, to be 23 feet, and the area of contamination is equal to 50 percent of the area of the sub-excavation sampling [i. e., 2340  $\text{feet}^2$  (217  $\text{meters}^2$ )], the total fuel present in the clay is calculated to be 711 pounds (323 kg). This figure is 20 percent of the total previously calculated for the sub-excavation zone [7880 pounds (3574 kg)]. Based on the single boring, therefore, residual fuel in the clay layer underlying the tank excavation appears unlikely to add more than 20 percent to the sub-excavation total, which corresponds to 4 percent to the total for the three venting zones. When the effect of soil analysis underestimation is included, this factor would contribute up to 5 percent underestimation.

- g. Fuel vapors were drawn from outside the vented zone.

It appears likely that at least some fuel vapors were drawn from areas whose soil hydrocarbon concentrations were not sampled and characterized. Measurement of pressure fields during venting tests suggests that vapors could have been drawn into the vertical vent wells from considerably further than the extent of the sampled zone. Moreover, relatively high vapor hydrocarbon concentrations were observed in vent well V2 and in the southernmost lateral vent (21) following venting. These elevated concentrations may indicate that vapors were drawn from north of V2 (i. e., beneath the waste oil garden) and southeast of the tank

excavation (perhaps from earlier spills from the fuel pump station). The hydrocarbon distribution of samples collected from V2 and V3 differed from those of the rest of the vertical vent field, indicating that additional petroleum products were present in the soil near the waste oil garden; a likely source is past spillage or leakage from the tanks or pipelines leading to the garden. However, there is not enough information to estimate the quantity of additional fuel vapors which could have been drawn into the vent system from beyond the vent fields.

In summary, no single hypothesis appears to account for the entire 268 percent difference in hydrocarbon masses determined from gas and soil analyses. Probably the difference results from several of the factors acting in concert. We conclude that the primary cause of the discrepancy between off-gas and soil hydrocarbon masses is venting of soil beyond the lateral and vertical extent of the vent field. This extended zone of venting influence is assumed to have drawn fuel vapors from zones of residual hydrocarbon contamination beyond the bounds of the recorded January 1985 JP-4 spill.

#### **5. Groundwater Analysis for Petroleum Constituents**

To determine whether venting had any adverse effect on quality of groundwater at the site, samples were collected from the on-site monitoring well RST-1 in early October 1989 after termination of venting, and were analyzed for volatile and semivolatile organic constituents. No volatile or semivolatile constituents were found. Particular constituents which were analyzed, and which would be expected to be present in petroleum distillates, are summarized in Table 7 of Appendix G. Results indicate that no transfer of petroleum hydrocarbons from the soil to underlying groundwater occurred as a result of the venting process.

#### **K. COSTS**

The costs of ISSV systems are site-specific, the magnitude of which will depend upon the scope of each activity undertaken (e.g., the size of the spill and length of time necessary of the remediation). Capital costs are usually low, with major items including the number and depth of vents, blowers, valving, piping, instrumentation, and air emissions control if necessary. Since the systems are not labor-intensive, operating costs are relatively low. Major operating costs are sampling, sample analysis, power, maintenance, and emissions control. Emissions control, if required, can add significantly to the cost. Other major costs in site cleanup will include preparation of plans for site cleanup, permitting, and performance monitoring. The various costs associated with ISSV systems are discussed in more detail in Volume II.

Based upon the experience of this research activity, an estimate was made of the costs of remediating a jet fuel spill site, such as at Hill AFB, by ISSV. For this estimate, the assumptions were that the site characterization, risk assessments, and feasibility studies had already been performed and, consequently, ISSV had been chosen as the technology to be used for remediation. Only those elements of cost deemed necessary for remediation of the site were included.

Two cost estimates were produced, one for a 1-year remediation time and the other for a 2.6-year remediation time (see Table 26). These periods correspond to equilibrium removal of contaminants as predicted by the equilibrium model described in Section V.D. with the input of a JP-4 standard composition (1 year) and a composition based on a subset of the Hill AFB pre-venting characterization samples (2.6 years). The air flow rate was set at 1500 scfm (0.71 scmm) in both cases. It is evident from the results of the post-venting characteristic studies that remediation of the

Hill AFB site will be complete at an intermediate point in the range of 1 to 2.6 years. The estimates presented below thus provide a reasonable estimate of the range of costs for similar fuel spills.

Based upon a 26,000-gallon (98,400-liter) spill in a 120 x 120 x 50 feet (36.6 x 36.6 x 15.2 meters) soil zone at the Hill AFB site, the total cost range of \$741,000 to \$1,019,000 translates to specific costs of \$4.2 to \$5.8 per pound of hydrocarbon removed, or \$27.5 to \$37.8/yard<sup>3</sup> of soil treated. These specific costs are comparable to those reported for other ISSV applications. For example, costs for treatment of TCE (trichlorethylene) spills have been given as \$15 to \$20/yard<sup>3</sup> of soil (Reference 4), and \$2.8/pound of TCE and \$8/pound of TCE with no emissions control and with carbon for emissions control, respectively (Reference 33). For the general case, a range of \$10 to \$50/yard<sup>3</sup> of soil was estimated (Reference 34), and a cost of \$73/pound was given for a 400-gallon gasoline spill (Reference 35).

As discussed previously, this cost estimate corresponds to cleanup times of 1 and 2.6 years for a spill site similar to that at Hill AFB. The cleanup time for such a site could be longer or shorter depending upon the number of vents, the capabilities of the blowers, and the efficiency of venting (that is, the ideality of contact of air and contaminants in the soil, the actual contaminant mixture, and soil properties). As seen above, the cost of the site remediation will vary with the cleanup time. With proper choice of flow capacity, emissions control type, and number and type of vents, an ISSV system could be designed which would produce a minimum total cost. The spreadsheet described in the economics section of Volume II would be very useful in such an optimization study.

For a 26,000-gallon (97,700-liter) JP-4 jet fuel spill, such as at Hill AFB, the spreadsheet of Volume II predicts a value of approximately \$6/pound for remediation by soil venting with catalytic oxidation as the emissions control option without pilot test, confirmatory sampling, or vent installation. This spreadsheet uses standard cost estimating methods, such as using installation factors for the major capital equipment items, estimating indirect costs (overhead) as a fraction of certain operating expense items, and depreciating the capital equipment costs over a certain lifetime. As seen above for the cost estimate developed in this section, an attempt was made to itemize most of the cost items, overhead costs were not included, and the total cost of the capital equipment was included in the remediation cost estimate. Considering the differences in the two cost estimating methods, the final cleanup cost values agreed reasonably well.



TABLE 26. COST ESTIMATE FOR REMEDIATION OF 26,000 GALLONS JP-4  
SPILL BY SOIL VENTING

Item	1-Year Cost (\$K)	2.6-Year Cost (\$K)
Project management (0.5 man-years/year)	60	156
Preparation of project plans and permit request (8 man-months)	80	80
Pilot test		
Vent and pressure monitoring well installation (1 vent and 10 pressure wells)	10	10
Equipment		
Blower (250 cfm)	4	4
Piping	1	1
Emissions control	10	10
Instrumentation	12	12
Assembly	15	15
Operation (1.5 man-months)	15	15
Sample analysis (6 samples)	1.5	1.5
Pilot test subtotal	68.5	68.5
Full-scale system installation		
Full-scale design (4 man-months)	40	40
Vent well installation (14 wells)	15	15
Equipment		
Blowers and flame arrestors (2 @ 1000 cfm)	18	18
Piping	50	50
Emissions control	90	90
Instrumentation (addition to pilot)	5	5
Installation (6 man-months)	60	60
Full-scale system subtotal	278	278

TABLE 26. COST ESTIMATE FOR REMEDIATION OF 26,000 GALLONS JP-4  
SPILL BY SOIL VENTING (CONCLUDED)

Item	1-Year Cost (\$K)	2.6-Year Cost (\$K)
Operating costs		
Manpower (0.5 man-years/year)	60	156
Electricity (25 hp)	17	43
Fuel (6,000 gallons/month)	31	81
Sample analysis (2/month)	6	16
Operating costs subtotal	114	296
Termination of Operation		
Confirmatory sampling	25	25
Sample analysis (100 samples)	25	25
Equipment demobilization	50	50
Reporting (4 man-months)	40	40
Termination subtotal	140	140
Total costs	\$741	\$1019

## SECTION VI

### CONCLUSIONS

This study demonstrated that *in situ* soil venting is effective for remediation of jet fuel spill sites in sandy soils. The experience gained during this test has provided additional information and insight into the applicability and factors controlling soil venting systems. Several major points are discussed in the following paragraphs.

Pilot testing proved extremely valuable for implementation of the full-scale system. *In situ* permeability tests proved to be a reasonable method for quick and inexpensive but accurate determination of air permeability at various points in the soil. A single-vent pilot test allowed measurement of expected extracted gas hydrocarbon concentrations as well as site data regarding the effect of soil conditions upon vacuum requirements and flow distribution. It is recommended that future pilot tests be operated for longer periods and include a shutdown, equilibration, and restart for determination of the importance of diffusion upon removal under the site conditions. Bench-scale testing did not prove to be useful for accurate extrapolation for prediction of full-scale remediation; however, bench-scale tests are urged for determination of empirical site-specific relations between soil contaminant concentration and equilibrated gas concentration that would be extremely useful in evaluation of the extent of cleanup during operations.

This demonstration showed soil venting to be very effective for JP-4 hydrocarbon removal. During the 9 months of operation, volatilization removed 105,000 pounds (47,600 kg), and another 15,000 to 20,000 pounds (6800 to 9100 kg) were assumed to have been converted by biodegradation. This corresponds to 68 to 72 percent removal of the initial spill mass, of which an unknown value remained at the commencement of operation. Soil hydrocarbon levels were reduced by 95 percent, and a corresponding drop of 99 percent was noted in soil gas levels. Only 7 percent of the post-operation soil samples exhibited total hydrocarbon levels greater than the 100 mg/kg limit that is used by several states. Moisture and clay content could not be related to lower removal efficiencies in this test. Shallower soil zones and areas with greater air flow received greater treatment.

Hydrocarbon removal rates from the full-scale Hill AFB system were found to be reasonably well-predicted using a simple, single equilibrium-stage Raoult's Law model. This type of model, demonstrated in the bench-scale column studies of Marley and Hoag (Reference 16) and suggested for projection of removal by Johnson et al. (Reference 17), has now been demonstrated at the field scale. Agreement between model and results during this demonstration was facilitated by relatively simple geohydrology and operation of vents centrally located in the contaminated area. Sites containing features which would cause deviation from equilibrium predictions due to poor air flow/contaminant contact, such as floating free product, contaminant in or on less permeable layers, or poor geometry of vent within the contaminated soil volume, may be treated with an equilibrium model as suggested by Johnson et al. (Reference 17) through the use of an empirically-derived efficiency factor. Equilibrium modelling may thus provide a simple tool for order-of-magnitude projections of site cleanup schedules. An alternative means of accurate projection would require two- or three-dimensional coupled flow and contaminant transport modeling, such as presented by Wilson et al. (Reference 18).

Application of equilibrium models to venting of JP-4 contamination shows that there is a heavy fraction of the fuel that is not readily volatilized. For instance, at a soil temperature of 60°F (15.6°C), about 350 liters of air per initial gram of fuel is necessary for 80 percent removal by volatilization only. The value for 90 percent removal is about 800 liters per gram, and for 95 percent removal is about 1500 liters per gram. The removal of the last 10 to 20 weight percent of the initial spill by volatilization will thus greatly lengthen operations and increase remediation costs. This remaining portion of the hydrocarbons will be stripped of the compounds of greatest environmental concern and will be the least mobile by volatilization and other transport mechanisms. Depending on the regulatory requirements governing a given site remediation, further contaminant removal by another mechanism may be necessary for complete remediation.

Biodegradation enhanced by soil aeration provided by *in situ* soil venting may provide the means of removal of the heaviest portion of JP-4, allowing the effective application of the soil venting to this hydrocarbon mixture. This demonstration has provided conclusive evidence that aerobic biodegradation of the hydrocarbons in the soil was occurring at significant rates. Biodegradation proceeded at a rate of about 18 percent of the volatilization rate with no effort made toward optimization of the process, by such means as reducing extraction rates, injection of nutrients, moisture addition, etc.

Soil heating provides a means for enhancement of hydrocarbon removal by venting, and another means for removal of less volatile components. The seven-week test of heated air injection using waste heat from catalytic oxidizer stack gas has indicated the feasibility of this technique. A measurable enhancement of removal due to heating was detected. These results suggest that a venting system designed with a uniform flow field for even soil heating could remediate a site several times faster than an unheated case, with favorable economics.

Based upon a hypothetical regulatory closure criterion of 100 mg/kg of hydrocarbons remaining in the soil (i. e., the limit set for several states), the vertical vented site and soil pile probably would have met regulatory requirements for closure at the end of this demonstration. The post-venting soil sampling was not designed for regulatory purposes (samples were collected in a regular pattern rather than randomly); however, the mean of the analyzed residual hydrocarbon concentrations of 50 mg/kg (SE 7 mg/kg) would meet the EPA's published criterion for comparison with an action level.

The total quantity of hydrocarbons measured in the vented air stream [105,000 pounds (47,600 kg)], and the quantity measured by difference between pre- and post-venting soil samples [39,000 pounds (17,750 kg)], differ by a factor of nearly 2.7. We hypothesize that this difference is largely due to withdrawal of fuel vapors from a zone larger than the zone defined by the soil samples which were collected from boreholes. The magnitude of difference between these two numbers, in a system which was relatively uniform geologically and from which several hundred soil samples were analyzed, suggests that in most cases it will be unrealistic to expect that pre-venting soil analyses will yield an accurate measure of extractable hydrocarbons.

The difficulty in establishing an accurate hydrocarbon mass balance in this and other venting studies suggests that methods to supplement pre-venting soil characterization are needed to assess the length of time required for fuel residue removal to a prespecified action level. One promising method would be to perform bench studies to derive site-specific correlations of equilibrated soil gas hydrocarbon concentrations to soil hydrocarbon concentrations as a function of the volume of gas drawn through a soil volume. A test protocol could be set which would define a necessary shutdown

period for equilibration, followed by extraction of gas from points distributed throughout the vented site. These gas samples would be analyzed and compared to the pre-established action level by use of the gas/soil hydrocarbon concentration correlation developed in bench studies. To be useful for predicting duration of remediation, it would be necessary to demonstrate by geologic examination of borehole logs that soil vapors would in fact be sampled by monitoring probes, and would not be subjected to flow restrictions due to saturated soil or intervening clay layers.

The use of bench-scale testing and subsequent vapor monitoring may also prove applicable to final confirmation of site regulatory acceptability. To be used for this purpose, the site-specific plan for comparison with the action level (e. g., testing protocols, numbers and depths of vapor monitoring probes, statistical treatment of vapor measurements) would need to be negotiated with regulators prior to initiation of venting. Given these caveats, application of gas/soil hydrocarbon concentration correlations derived from bench-scale tests may prove both as effective as, and less costly than, post-venting sampling for determination of compliance of soil venting with regulatory action levels.

An estimate of the range of remediation cost for the Hill AFB site was made using an equilibrium removal model, assuming initial mass equal to the total initial spill amount. Volatilization of 80 percent of the initial spill was specified, with an estimated additional 15 percent destruction by biodegradation, which would result in an averaged soil concentration of less than 100 mg/kg total hydrocarbons. For this case, a range of 1 to 2.6 years of operation would be required, at a total estimated cost of \$741,000 to \$1,019,000 which translates to \$4.2 to 5.8 per pound of hydrocarbon removed, or approximately \$27.5 to \$37.8/yard<sup>3</sup> of soil treated. The results of post-venting soil sampling suggest that the Hill AFB remediation would fall on the lower portion of the cost range. The application of these cost numbers to other sites would not be possible without suitable information regarding the air permeability of the soil, total spill volume, and contaminant characteristics. Nevertheless, *in situ* soil venting may be seen as a prospect for effective and cost-efficient means of remediation of JP-4 jet fuel at most Air Force sites.

## SECTION VII

### RECOMMENDATIONS

Based upon the results of this demonstration, several recommendations are offered for further testing and application of *in situ* soil venting, as listed below.

- In situ soil venting has proven to be effective in removal of JP-4 from sandy unsaturated soils in this field study. Therefore, the technology may be considered for remediation of jet fuel and other more volatile contaminants at spill sites.
- Prior to the start of a soil venting implementation, a user should contact the proper regulatory agencies to determine the necessary cleanup standards the technology must meet. Soil venting will be much more attractive if the standards are based upon such performance criteria such as equilibrium soil gas levels or groundwater levels in equilibrium with soil gas rather than individual compounds.
- Site characterization is important for proper application of the technology. An estimate of the air permeability of the soil is extremely helpful for design of a pilot system.
- Pilot testing should be conducted at a potential soil venting site prior to full-scale system design for investigation of the effect of soil conditions upon subsurface air flow (including but not limited to a measure of the air permeability of the soil) and expected extracted gas contaminant concentration. A pilot system should be operated long enough so that a shutdown test may be conducted in order to determine if great deviations from equilibrium removal are to be expected. Such a determination will be extremely useful in projecting cleanup schedule.
- This demonstration exhibited significant contributions of biodegradation toward hydrocarbon removal despite less than optimum conditions for bioactivity. Future efforts should focus upon enhancing the rate of biodegradation relative to volatilization. Such efforts will be fruitful both for reducing costs by reducing emissions control requirements and for converting the least volatile fuel components. All venting applications should employ some means for documentation of bioactivity, such as monitoring of carbon dioxide generation and oxygen depletion in the extracted gas.
- Enhancement of removal by heating shows promise both as a means of accelerating site cleanups and application of soil venting to sites with less permeable soil or less volatile contaminants. Continued field study, coupled with contaminant/heat transport modeling, is urged.

- Although this demonstration proved *in situ* soil venting to be effective for removal of JP-4 from sandy soils in a relatively simple geohydrological setting, field testing should continue for investigation of JP-4 and other contaminant removal in less optimal removal cases. Situations of interest would include less permeable soils, moister soils, and a free product layer on groundwater. Such field tests should be conducted for long periods to prove feasibility of site cleanup as well as high removal capabilities.
- Although a simple Raoult's Law equilibrium model adequately described removal for this demonstration, such an approach would probably not be suitable for all situations. Coupled air flow/contaminant transport models should be developed for more accurate prediction of site cleanup. With this goal, bench testing should continue for determination of the importance of various factors such as moisture, soil organic content, contaminant type, diffusion, etc. upon removal mechanism and rate.

## SECTION VIII

### REFERENCES

1. Bennedsen, M. D., Scott, J. P., and Hartley, J. D., "Use of Vapor Extraction Systems for *In Situ* Removal of Volatile Organic Compounds from Soil," Proc. Nat. Conf. Hazardous Waste and Hazardous Materials, Washington, D.C., 16-18 March 1987, pp. 92-95.
2. Foster Wheeler Enviresponse, Inc., Superfund Innovative Technology Evaluation Technology Demonstration Summary - Terra-Vac<sup>®</sup> *In Situ* Vacuum Extraction System, Groveland, Massachusetts, EPA/540/S5-89/003, May 1989.
3. Crow, W. L., Anderson, E. P., and Minugh, E. M., Subsurface Venting of Vapors Emanating from Hydrocarbon Product on Groundwater, Final Report American Petroleum Institute, September 1985.
4. Crow, W. L., Anderson, E. P., and Minugh, E. M., "Subsurface Venting of Vapors Emanating from Hydrocarbon Product on Groundwater," Groundwater Monitoring Review, Vol. 7, Winter 1987, pp. 51-57.
5. Anastos, G. J., Marks, P. J., Corbin, M. H., and Coia, M. F., *In Situ* Air Stripping of Soils Pilot Study, Final Report, AMXTH-TE-TR-85026, U.S. Army Toxic and Hazardous Materials Agency, October 1985.
6. Rollins, Brown and Gunnell, Inc., Subsurface Investigation and Remedial Action: Hill Air Force Base JP-4 Fuel Spill, Provo, Utah, December 1985.
7. Feth, J. H., Barker, D. A., Moore, L. G., Brown, R. J., and Veirs, C. E., "Lake Bonneville: Geology and Hydrogeology of the Weber Delta District, Including Ogden, Utah." U. S. Geological Survey Professional Paper 518, U. S. Government Printing Office, Washington, D.C., 1966.
8. Gardner, W. H., "Water Content," in Methods of Soil Analyses, Part 1, Physical and Mineralogical Methods, ed A. Klute, 2nd Edition, American Society of Agronomy, Inc. and Soil Science Society of America, Inc., Madison, Wisconsin, pp. 493-544, 1982.
9. Hillel, D., Fundamentals of Soil Physics. Orlando: Academic Press, Inc., 1980.
10. U. S. Environmental Protection Agency, Test Methods for Evaluation of Solid Wastes, SW-846 (3rd Ed.), Washington, D.C., November 1986.
11. McCabe, W. L. and Smith, J. C., Unit Operations of Chemical Engineering, McGraw-Hill, New York, 1976.
12. Solomon, D. K., and Cerling, T. E., 1987. "The Annual Carbon Dioxide Cycle in a Montana Soil: Observations, Modeling, and Implications for Weathering," Water Resources Res., Volume 23, pp. 2257-2265.



REFERENCES  
(CONTINUED)

13. Krishnappa, A. V., O'Connor, J. J., Agar, J. G., and King, R. D., "Vapor Extraction Systems - Factors Affecting - Their Design and Performance," Proc. NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, Texas, 9-11 November 1988, pp. 547-569.
14. Weston, Roy F., Inc., Task Order 4. Laboratory Study of *In Situ* Volatilization (ISV) Technology Applied to Fort Campbell Soils Contaminated with JP-4, DAAK 11-85-D-0007, March 1987.
15. Thornton, J. S. and Wootan, W. L., Jr., "Venting for the Removal of Hydrocarbon Vapors from Gasoline Contaminated Soil," J. Environ. Sci. Health A17(1), pp. 31-44, 1982.
16. Marley, M. C. and Hoag, G. E., "Induced Soil Venting for Recovery/Restoration of Gasoline Hydrocarbon in the Vadose Zone," Proceedings of NWWA/API Conf. on Petroleum Hydrocarbons and Org. Chemicals in Groundwater - Prevention, Detection and Restoration, November 1984, pp. 473-503.
17. Johnson, P. C., Kemblowski, M. W., and Colthart, J. D., "Quantitative Analysis for the Cleanup of Hydrocarbon-Contaminated Soils by In-Situ Soil Venting Systems," Ground Water, Vol. 28, No. 3, pp. 413-429, May-June 1990.
18. Wilson, D. J., Clarke, A. N., and Clarke, J. H., "Soil Clean Up by *In Situ* Aeration. I. Mathematical Modeling," Sci. Tech., 23(10&11), pp. 991-1037, 1988.
19. Reid, R. C., Prausnitz, J. M., Sherwood, T. K., The Properties of Gases and Liquids, Third Edition, McGraw-Hill, New York, 1977.
20. Johnson, J. J. and Sterrett, R. J., "Analysis of *In Situ* Soil Air Stripping Data," Proc. Fifth National Conf. on Hazardous Wastes and Hazardous Materials, Las Vegas, Nevada, 19-21 April 1988, pp. 451-455.
21. Lee, M. D. et al., Bioremediation of Aquifers Contaminated With Organic Compounds. CRC Critical Reviews in Env. Control. Vol. 18, pp. 29-89, 1988.
22. Hinchee, R. E., Downey, D. C., Slaughter, J. K., and Westray, M., Enhanced Bioremediation of Jet Fuels: A Full Scale Test at Eglin Air Force Base, Florida. Air Force Engineering and Services Center Report ESL TR 88-78, August 1989.
23. Downey, D. L., Hinchee, R. E., Westray, M. S., and Slaughter, J. K., "Combined Biological and Physical Treatment of a Jet Fuel-Contaminated Aquifer," Proceedings of NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, pp. 627-645, November 1988.

REFERENCES  
(CONCLUDED)

24. Wilson, J. S. and Conrad, S. H., "Is Physical Displacement of Residual Hydrocarbons a Realistic Possibility in Aquifer Restoration," Proceedings of NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, November 5-7, 1984, National Water Well Association, Worthington, Ohio.
25. Atlas, R. M., "Microbial Degradation of Petroleum Hydrocarbons: An Environmental Perspective," Microbiol. Rev., Vol. 45, pp. 180-209, 1986.
26. American Petroleum Institute, Field Study of Enhanced Subsurface Biodegradation of Hydrocarbons Using Hydrogen Peroxide as an Oxygen Source, API Publication No. 4488, Health and Environmental Sciences Department, Washington, D.C., 1987.
27. Healy, J. B. and Daughton, C. G., Issues Relevant to Biodegradation of Energy-Related Compounds in Ground Water, UCB/SEEHRL 86-10, U.S. Department of Energy, Bartlesville, Oklahoma, 1986.
28. Hoefs, J., Stable Isotopic Geochemistry, Springer Verlag, New York, 1981.
29. Ely, D. L. and Heffner, D. A., Process for In Situ Biodegradation of Hydrocarbon Contaminated Soil, U.S. Patent Number 4,765,902, August 23, 1988.
30. Ghassemi, M., "Innovative In Situ Treatment Technologies for Cleanup of Contaminated Sites," presented at Third Annual Hazardous Waste Law and Management Conference, Seattle, Washington, and Portland, Oregon, October 1986.
31. Wilson, J. H., Counce, R. M., Lucero, A. J., Jennings, H. L., and Singh, S. P., Air Stripping and Emissions Control Technologies: Field Testing of Countercurrent Packings, Rotary Air Stripping, Catalytic Oxidation, and Adsorption Materials, ESL TR 90-51, Air Force Engineering and Services Center, Tyndall AFB, Florida, 1992.
32. Johnson, P. C., Kemblowski, M. W., Colthart, J. D., Byers, D. L., and Stanley, C. C., "A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems," Ground Water Monitoring Review, Vol. 10, pp. 159-179, Spring 1990.
33. Oster, C. C., Connell, P., and Wenck, M., "Vacuum Extraction of Volatile Organics from Soils," Proc. Industrial Wastes Symposia, WPCF 61st Annual Conf., Dallas, Texas, 1982, pp. 1-8.
34. Marley, M. G., Richter, S. D., Cliff, B. L., and Nangeroni, P. E., "Design of Soil Vapor Extraction Systems - A Scientific Approach," Appendix E of Soil Vapor Extraction Technology Reference Handbook, EPA/540/2-91/003, pp. 240-251, February 1991.
35. Connor, J. R., "Case Study of Soil Venting," Pollution Engineering, Vol. 20(7), pp. 74-78, July 1988.

APPENDIX A  
PRE-VENTING SITE CHARACTERIZATION

TABLE A-1. SOIL CHARACTERISTICS: EXCAVATION BORINGS AND BORINGS 31 (V7) AND 41

Borehole No.	Nominal Depth (ft)	Soil Fractionation (Wt %)*			Moisture (% Dry Wt)	Bulk Dens (g/cm <sup>3</sup> )**	Porosity††	
		Gravel	Sand	Silt			Porosity†	Air-filled Porosity††
3	1	0.3	92.7	3.0	5.64	N/D	N/D	N/D
3	7	2.6	90.6	1.0	6.78	N/D	N/D	N/D
3	12	0.0	12.0	58.0	26.37	N/D	N/D	N/D
24	1	21.5	69.1	4.7	9.73	N/D	N/D	N/D
24	7	0.2	91.8	2.0	6.33	N/D	N/D	N/D
24	10	13.4	60.6	13.9	13.85	N/D	N/D	N/D
24	11	0.2	28.0	42.6	26.23	N/D	N/D	N/D
25	1	20.7	73.7	0.8	7.14	N/D	N/D	N/D
25	7	1.0	69.0	5.0	11.18	N/D	N/D	N/D
25	12	0.3	29.9	41.9	28.11	N/D	N/D	N/D
29	1	0.8	81.4	9.9	10.39	N/D	N/D	N/D
29	7	0.7	89.3	5.0	17.19	N/D	N/D	N/D
29	12	0.0	18.0	54.0	28.0	N/D	N/D	N/D
31	1	4.1	72.9	12.5	10.5	N/D	N/D	N/D
31	5	5.2	85.4	2.8	3.93	1.44	0.46	0.40
31	10	33.3	62.0	0.7	1.47	1.75	0.34	0.31
31	15	0.1	89.0	5.0	-0.02	1.99	0.25	0.25
31	20	2.9	90.3	1.0	0.08	1.54	0.42	0.42
31	25	1.5	84.7	6.9	0.07	1.71	0.35	0.35
31	30	0.6	80.5	10.9	0.14	1.76	0.34	0.33
31	35	0.4	94.6	2.0	1.85	1.80	0.32	0.29
31	40	0.1	95.0	0.1	0.01	1.48	0.44	0.44
31	45	5.8	87.6	0.9	0.56	1.67	0.37	0.36
31	50	27.0	67.9	0.7	0.03	1.58	0.40	0.40
41	1	5.0	73.1	12.4	0.19	1.95	0.26	0.26
41	5	2.3	85.0	4.9	3.01	1.66	0.37	0.32
41	10	6.3	23.4	47.8	2.19	1.57	0.41	0.37
41	15	0.1	92.9	1.0	20.45	1.58	0.40	0.08
41	20	1.0	92.9	2.0	3.55	1.49	0.44	0.39
41	25	0.2	92.8	1.0	2.52	1.65	0.38	0.34
41	30	1.9	91.2	2.0	-0.03	1.65	0.38	0.38
41	35	0.0	17.0	55.0	0.01	1.70	0.36	0.36
					19.35	1.73	0.35	0.01

**TABLE A-1. SOIL CHARACTERISTICS: EXCAVATION BORINGS AND BORINGS 31 (V7) AND 41 (CONCLUDED)**

TABLE A-2. VARIABILITY OF MOISTURE CONTENT  
IN FIELD SOIL SAMPLE REPLICATES

Borehole	Depth BLS (ft)		Water Content		C. V.	
No.	Top	Bottom	(% Dry Wt)	Mean (%)	S. E. (%)	(% of mean)
1	10.5	12	6.11	5.47	0.91	16.63
1	10.5	12	4.82			
2	23.5	25	10.12	7.51	3.69	49.06
2	23.5	25	4.91			
3	13.5	15	7.17	6.73	0.61	9.11
3	13.5	15	6.30			
4	18.5	20	4.51	4.87	0.52	10.58
4	18.5	20	5.24			
5	4.5	5	4.29	4.09	0.16	3.79
5	4.5	5	3.98			
6	13.5	15	4.60	6.65	2.89	43.53
6	13.5	15	8.70			
9	4.5	6	5.41	6.86	0.64	9.36
9	4.5	6	7.31			
10	13.5	15	15.66	10.94	6.67	60.96
10	13.5	15	6.23			
14	13.5	15	5.93	5.15	1.11	21.55
14	13.5	15	4.36			
E	13.5	15	4.50	4.58	0.11	2.47
E	13.5	15	4.66			
Y	4.5	6	4.47	4.57	0.13	2.82
Y	4.5	6	4.66			
					Mean:	20.90

TABLE A-3. MOISTURE CONTENT OF SAMPLES FROM VENT WELL BORINGS

Gr. Junct.	Borehole	Depth BLS (ft)		Water Content
Samp. No.	No.	Top	Bottom	(% Dry Wt)*
4104	V2	1.5	3	2.81
4106	V2	4.5	6	5.67
4108	V2	7.5	9	5.71
4110	V2	10.5	12	4.43
4112	V2	13.5	15	5.15
4114	V2	18.5	20	4.35
4116	V2	23.5	25	10.12
4118	V2	23.5	25	4.91
4120	V2	28.5	30	3.63
4122	V2	33.5	35	6.35
4124	V2	38.5	40	N/D
4125	V2	43.5	45	N/D
4127	V2	45	45.5	N/D
4128	V2	48.5	50	25.53
4130	V1	1.5	3	2.49
4132	V1	4.5	6	4.25
4134	V1	7.5	9	4.32
4136	V1	10.5	12	6.11
4138	V1	10.5	12	4.82
4140	V1	13.5	15	N/D
4140	V1	13.5	15	4.92
4143	V1	18.5	20	N/D
4145	V1	23.5	25	N/D
4147	V1	28.5	30	N/D
4149	V1	33.5	35	N/D
4151	V1	38.5	40	N/D
4153	V1	43.5	45	N/D
4155	V1	48.5	50	14.81
4157	V3	1.5	3	6.87
4159	V3	4.5	6	5.14
4161	V3	7.5	9	5.82
4163	V3	10.5	12	3.82
4166	V3	13.5	15	7.17
4167	V3	13.5	15	6.30
4169	V3	18.5	20	
4171	V3	23.5	25	4.44
4173	V3	28.5	30	
4173	V3	28.5	30	4.61
4175	V3	33.5	35	3.87
4176	V3	37.5	38	6.56
4178	V3	38.5	40	3.64
4180	V3	43.5	45	N/D
4182	V3	48.5	50	24.17
4184	V4	1.5	3	6.56
4186	V4	4.5	6	5.10

TABLE A-3. MOISTURE CONTENT OF SAMPLES FROM VENT WELL BORINGS  
(CONTINUED)

Gr. Junct. Samp. No.	Borehole No.	Depth BLS (ft)		Water Content (% Dry Wt)*
		Top	Bottom	
4189	V4	7.5	9	3.89
4191	V4	10.5	12	4.17
4193	V4	13.5	15	N/D
4193	V4	13.5	15	5.31
4196	V4	17.5	18	5.24
4195	V4	18.5	20	4.51
4197	V4	18.5	20	N/D
4197	V4	18.5	20	5.24
4199	V4	23.5	25	7.73
4201	V4	28.5	30	3.27
4203	V4	33.5	35	26.22
4205	V4	35.5	40	26.28
4207	V4	43.5	45	23.27
4209	V11	1.5	3	7.30
4211	V11	4.5	6	5.25
4213	V11	7.5	9	4.45
4215	V11	10.5	12	26.89
4218	V11	13.5	15	4.82
4220	V11	18.5	20	4.97
4222	V11	23.5	25	N/D
4224	V11	28.5	30	4.78
4225	V11	35.5	36	N/D
4227	V11	38.5	40	N/D
4228	V11	38.5	40	N/D
4230	V11	43.5	45	N/D
4232	V15	7.5	9	5.68
4234	V15	10.5	12	N/D
4234	V15	10.5	12	10.76
4237	V15	13.5	15	6.33
4238	V15	10	10.5	5.83
4240	V15	18.5	20	5.78
4242	V15	23.5	25	N/D
4244	V15	28.5	30	N/D
4245	V15	28.5	30	N/D
4246	V15	32	32.5	N/D
4248	V15	33.5	35	23.46
4249	V15	37.5	38	N/D
4251	V15	38.5	40	N/D
4253	V15	43.5	45	N/D
4255	V15	48.5	50	N/D
4257	V8	1.5	3	N/D
4257	V8	1.5	3	5.84
4259	V8	4.5	6	6.12
4261	V8	7.5	9	5.45
4263	V8	10.5	12	6.14



TABLE A-3. MOISTURE CONTENT OF SAMPLES FROM VENT WELL BORINGS  
(CONTINUED)

Gr. Junct. Samp. No.	Borehole No.	Depth BLS (ft)		Water Content (% Dry Wt)*
		Top	Bottom	
4265	V8	13.5	15	17.13
4268	V8	18.5	20	N/D
4270	V8	23.5	25	N/D
4270	V8	23.5	25	2.18
4272	V8	26.5	30	N/D
4273	V8	27	27.5	N/D
4274	V8	28.5	30	N/D
4276	V8	33.5	35	N/D
4278	V8	38.5	40	3.47
4280	V8	43.5	45	2.97
4282	V8	48.5	50	N/D
4283	V8	46.5	47	N/D
4285	V12	1.5	3	2.30
4287	V12	4.5	6	4.80
4289	V12	7.5	9	4.90
4291	V12	10.5	12	6.36
4293	V12	13.5	15	5.60
4295	V12	18.5	20	N/D
4297	V12	23.5	25	N/D
4300	V12	28.5	30	N/D
4302	V12	33.5	35	N/D
4304	V12	38.5	40	N/D
4305	V12	38.5	40	N/D
4307	V12	43.5	45	N/D
4309	V12	48.5	50	N/D
4310	V12	47	47.5	N/D
4312	V13	1.5	3	4.49
4314	V13	4.5	6	4.80
4316	V13	7.5	9	4.48
4318	V13	10.5	12	5.85
4320	V13	12.5	13	5.29
4322	V13	13.5	15	10.39
4324	V13	19.5	20	N/D
4326	V13	23.5	25	N/D
4328	V13	28.5	30	N/D
4329	V13	27	27.5	N/D
4331	V13	33.5	35	N/D
4332	V13	32	32.5	N/D
4333	V13	33.5	34	N/D
4335	V13	38.5	40	N/D
4337	V13	43.5	45	N/D
4340	V14	1.5	3	6.41
4342	V14	4.5	6	4.78
4344	V14	7.5	9	3.71
4346	V14	10.5	12	4.78

TABLE A-3. MOISTURE CONTENT OF SAMPLES FROM VENT WELL BORINGS  
(CONTINUED)

Gr. Junct. Samp. No.	Screnhole No.	Depth BLS (ft)		Water Content (% Dry Wt)*
		Top	Bottom	
4349	V14	13.5	15	5.93
4350	V14	13.5	15	4.36
4352	V14	18.5	20	N/D
4354	V14	23.5	25	N/D
4356	V14	28.5	30	N/D
4358	V14	33.5	35	N/D
4360	V14	38.5	40	10.56
4362	V14	43.5	45	N/D
4364	V14	48.5	50	N/D
4367	V5	1.5	3	2.46
4369	V6	4.5	6	4.97
4371	V6	7.5	9	4.04
4373	V6	10.5	12	5.26
4376	V6	13.5	15	4.60
4377	V6	13.5	15	8.70
4379	V6	18.5	20	N/D
4379	V6	18.5	20	4.89
4381	V6	23.5	25	5.41
4383	V6	28.5	30	4.47
4385	V6	33.5	35	6.62
4387	V6	38.5	40	3.73
4389	V6	43.5	45	4.19
4391	V6	48.5	50	N/D
4391	V6	48.5	50	3.11
4393	V5	1.5	3	2.75
4396	V5	4.5	6	4.20
4397	V5	4.5	6	3.98
4399	V5	7.5	9	3.29
4401	V5	10.5	12	6.41
4403	V5	13.5	15	4.44
4405	V5	18.5	20	N/D
4407	V5	23.5	25	N/D
4408	V5	12.8	13	N/D
4410	V5	28.5	30	N/D
4412	V5	33.5	35	5.64
4414	V5	38.5	40	N/D
4416	V5	43.5	45	4.65
4418	V5	48.5	50	4.78
4422	Y	1.5	3	4.46
4424	Y	4.5	6	4.47
4426	Y	4.5	6	4.66
4428	Y	7.5	9	4.51
4430	Y	10.5	12	3.71
4432	Y	13.5	15	5.41
4434	Y	18.5	20	N/D

TABLE A-3. MOISTURE CONTENT OF SAMPLES FROM VENT WELL BORINGS  
(CONTINUED)

Gr. Junct. Samp. No.	Borehole No.	Depth dLS (ft)		Water Content (% Dry Wt)*
		Top	Bottom	
4436	Y	23.5	25	3.98
4438	Y	28.5	30	4.37
4440	Y	33.5	35	24.50
4442	Y	38.5	40	N/D
4444	Y	43.5	45	N/D
4446	Y	48.5	50	4.32
4448	Y	53.5	55	3.64
4450	Y	58.5	60	23.00
4452	Y	63.5	65	N/D
4454	Y			N/D
4455	Y	61	61.5	N/D
4461	E	1.5	3	8.77
4463	E	4.5	6	5.91
4465		7.5	9	4.98
4467	E	10.5	12	12.31
4469	E	13.5	15	4.50
4470	E	13.5	15	4.66
4472	E	18.5	20	N/D
4472	E	18.5	20	7.95
4474	E	23.5	25	5.60
4477	E	28.5	30	4.10
4479	E	33.5	35	5.14
4481	E	38.5	40	30.81
4483	E	43.5	45	25.90
4485	E	48.5	50	23.12
4487	E	53.5	55	28.95
4489	E	58.5	60	25.74
4490	E	57.2	57.5	N/D
4492	E	62	62.2	N/D
4499	V10	7.5	9	N/D
4499	V10	7.5	9	4.34
4501	V10	10.5	12	12.40
4504	V10	13.5	15	
4504	V10	13.5	15	15.66
4505	V10	13.5	15	6.23
4507	V10	18.5	20	7.37
4509	V10	23.5	25	6.67
4511	V10	28.5	30	6.47
4513	V10	33.5	35	4.62
4514	V10	38.5	39	N/D
4514	V10	39.5	39	N/D
4516	V10	39	40	29.94
4518	V10	43.5	45	26.45
4520	V10	48.5	50	23.54
4523	V9	1.5	3	11.61

TABLE A-3. MOISTURE CONTENT OF SAMPLES FROM VENT WELL BORINGS  
(CONCLUDED)

Gr. Junct.	Borehole	Depth B.S. (ft)		Water Content
Samp. No.	No.	Top	Bottom	(% Dry Wt)*
4526	V9	4.5	6	3.41
4527	V9	4.5	6	7.31
4529	V9	7.5	9	4.72
4531	V9	10.5	12	7.21
4533	V9	13.5	15	3.36
4535	V9	18.5	20	N/D
4535	V9	18.5	20	6.71
4537	V9	23.5	25	5.74
4539	V9	28.5	30	3.71
4541	V9	33.5	35	6.25
4543	V9	38.5	40	7.00
4545	V9	43.5	45	25.94
4547	V9	48.5	50	17.98
*(Wet Wt - Dry Wt)/Dry Wt x 100%				

TABLE A-4. MOISTURE CONTENT OF PRE-VENTING PILE SAMPLES

Gr. Junct. Samp. No.	Borehole No.	Depth BLS (ft)		Water Content (% Dry Wt)*
		Top	Bottom	
4562	P1	1.0	2.0	1.71
4563	P1	3.2	4.2	2.65
4564	P1	6.4	7.4	7.76
4558	P2	1.0	2.0	6.95
4559	P2	3.2	4.2	7.51
4560	P2	4.2	5.2	7.27
4561	P2	6.2	7.2	6.94
4565	P3	1.0	2.0	7.95
4566	P3	3.0	4.0	7.08
4567	P3	4.5	5.5	7.51
4548	P4	1.0	2.0	5.90
4549	P4	3.0	4.0	5.17
4550	P4	6.5	7.5	6.89
4551	P5	1.0	2.0	7.53
4552	P5	3.3	4.3	6.54
4553	P5	4.3	5.3	6.30
4554	P5	6.2	7.2	5.46
4555	P6	1.0	2.0	6.60
4556	P6	3.0	4.0	7.91
4557	P6	4.6	5.6	6.74
4569	P7	1.0	2.0	1.75
4570	P7	3.2	4.2	3.52
4571	P7	6.6	7.6	5.96
4572	P8	1.0	2.0	7.66
4573	P8	3.0	4.0	6.44
4574	P8	4.0	5.0	6.78
4575	P8	5.3	6.3	5.57
4576	P9	1.0	2.0	4.47
4577	P9	3.3	4.3	6.35
4578	P9	4.5	5.5	6.96
4579	P10	1.0	2.0	2.89
4580	P10	3.0	4.0	3.18
4581	P10	6.6	7.6	5.06
4582	P11	1.0	2.0	2.85
4583	P11	3.0	4.0	3.64
4584	P11	5.1	6.1	5.29
4585	P12	1.0	2.0	5.79
4586	P12	3.2	4.2	6.23
4587	P12	4.6	5.6	6.63
4588	T8	-	-	-0.50
*[(Gross Wet Wt - Gross Dry Wt)/(Gross Dry Wt - Tare)]*100				

TABLE A-5. VARIABILITY OF FIELD AND LABORATORY ANALYTICAL REPLICATES

ACD Sample No.		Pre- vs Post-vntg	HC Conc. (mg/kg)			S. E.	C. V. (%)	Log-transformed HC Conc.		S. E.	
Date	No. 1		No. 2	No. 1	No. 2			No. 1	No. 2		
LABORATORY REPLICATES											
880913	268	259	Pre	20400	8800	14600	56.2	4.310	3.944	4.127	0.258
880512	277	277	Pre	6300	6400	6350	7.1	3.799	3.806	3.803	0.005
880515	064	064	Pre	5300	6300	5800	707	3.724	3.799	3.762	0.053
881111	032	032	Pre	3300	3600	3450	212	3.513	3.558	3.537	0.027
881111	042	042	Pre	1500	5000	3250	2475	3.176	3.699	3.438	0.370
880831	144	144	Pre	2700	3000	2850	212	3.431	3.477	3.454	0.032
880909	170	170	Pre	1500	1900	1700	283	3.176	3.279	3.227	0.073
880823	068	068	Pre	1600	1540	1570	42	3.204	3.180	3.196	0.012
880913	266	266	Pre	1000	1130	1065	92	3.000	3.053	3.027	0.038
880823	065	065	Pre	580	1100	840	368	2.753	3.041	2.902	0.197
880823	055	055	Pre	710	940	825	163	2.851	2.973	2.912	0.086
880823	094	094	Pre	900	610	755	205	2.954	2.785	2.870	0.119
880824	053	053	Pre	360	400	380	28	2.556	2.602	2.579	0.032
881111	061	061	Pre	20	50	50	42	1.301	1.903	1.602	0.426
881111	052	052	Pre	40	30	35	7	1.602	1.477	1.540	0.088
880913	151	151	Pre	<20	<20	N/D*	N/D	N/D	N/D	N/D	N/D
880824	070	070	Pre	<20	<20	N/D	N/D	N/D	N/D	N/D	N/D
880831	138	138	Pre	<20	<20	N/D	N/D	N/D	N/D	N/D	N/D
Mean:							26.0	Mean:		0.121	
FIELD REPLICATES											
880913	266	269	Pre	1400	8800	5100	5233	3.146	3.944	3.545	0.565
871109	152	153	Pre	5500	1100	3300	3111	3.740	3.041	3.391	0.494
880817	084	085	Pre	5700	70	2885	3991	3.756	1.645	2.800	1.351
871109	124	125	Pre	2600	2300	2450	212	3.415	3.362	3.388	0.038
880909	168	169	Pre	1600	3000	2300	990	3.204	3.477	3.341	0.193
880915	060	061	Pre	2000	2300	2150	212	3.301	3.362	3.331	0.043

TABLE A-5. VARIABILITY OF FIELD AND LABORATORY ANALYTICAL REPLICATES  
(CONCLUDED)

ACD Sample No.			Pre- vs Post-vntg	HC Conc. (mg/kg)			S. E.	C. V. (%)	Log-transformed IIC Concs.				
Date	No.1	No.2		No.1	No. 2	Mean			No. 1	No. 2	Mean	S. E.	
871109	165	166	Pre	2100	2200	2150	71	3.3	3322	3342	3332	0.014	
871109	171	172	Pre	1700	2000	1850	212	11.5	3230	3301	3266	0.050	
871223	038	039	Pre	1100	2300	1700	849	49.9	3041	3362	3202	0.227	
880823	066	068	Pre	450	1540	995	771	77.5	2653	3188	2920	0.378	
871109	095	096	Pre	300	400	350	71	20.2	2477	2602	2540	0.088	
891107	043	044	Post	193	40	116.5	108	92.9	2286	1602	1944	0.483	
891107	036	037	Post	28	37	32.5	6	19.6	1447	1568	1508	0.086	
891106	257	258	Post	28	36	32	6	17.7	1447	1556	1502	0.077	
891107	052	053	Post	36	25	30.5	8	25.5	1556	1398	1477	0.112	
891106	236	237	Post	26	34	30	6	18.9	1415	1531	1473	0.082	
891102	274	275	Post	31	25	28	4	15.2	1491	1398	1445	0.066	
891106	031	032	Post	20	32	26	8	32.6	1301	1505	1403	0.144	
891102	268	269	Post	26	23	24.5	2	6.7	1415	1362	1389	0.036	
891107	049	050	Post	31	<20	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
880906	070	071	Pre	<20	<20	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
880901	061	062	Pre	<20	<20	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
880831	136	137	Pre	<20	<20	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
880826	098	099	Pre	<20	<20	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
880823	051	052	Pre	<20	10	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
880818	149	150	Pre	<20	<20	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
871223	049	050	Pre	<100	<100	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
							Mean:	41.6			Mean:	0.238	
*Not determined													

TABLE A-6. PRE-VENTING HYDROCARBON ANALYSES: BENEATH FUEL TANKS

Borehole No.	Depth BLS (ft)*		Samp. Type**	Total HC (mg/kg)	GJ Samp No.	ACD Samp No.	
	Top	Btm				Date	No.
1	1.5	3.5		100	011102701	871109	115
1	8.5	10.5		100	011102708	871109	116
1	13.5	14.1	B	1000	011102713	871109	117
3	1.5	2.5		<100	031103701	871109	118
3	7.5	8.5		<100	031103707	871109	119
3	12.8	13.3	B	<100	031103712	871109	120
5	1.5	2.5		2400	051103701	871109	121
5	7.5	8.5		1500	051103707	871109	122
5	12.5	13.0	B	200	051103712	871109	123
12	1.5	2.5		2600	121104701	871109	124
12	1.5	2.5	F	2300	121104701R	871109	125
12	7.5	8.5		3200	121104707	871109	126
12	12.6	13.2	B	300	121104712	871109	127
16	0.0	1.0		1400	161104700	871109	084
16	1.0	2.0		2500	161104701	871109	085
16	2.0	3.0		5500	161104702	871109	086
16	3.0	4.0		5000	161104703	871109	087
16	4.0	5.0		5400	161104704	871109	086
16	5.0	6.0		6400	161104705	871109	089
16	6.0	7.0		4700	161104706	871109	090
16	7.0	8.0		3800	161104707	871109	091
16	8.0	9.0		1100	161104708	871109	092
16	9.0	10.0		200	161104709	871109	093
16	10.0	11.0		1100	161104710	871109	094
16	11.0	12.0		300	161104711	871109	095
16	11.0	12.0	F	400	161104711R	871109	096
16	12.0	13.0		100	161104712	871109	097
16	13.0	14.0		600	161104713	871109	098
16	14.0	15.0		600	161104714	871109	099
16	15.0	16.0		400	161104715	871109	100
16	16.0	17.0		800	161104716	871109	101
18	1.5	2.7		100	181104701	871109	128
18	7.5	8.2		5000	181104707	871109	129
18	12.5	13.0	B	200	181104712	871109	130
23	2.5	3.5		900	231105702	871109	164
23	7.5	8.6		2100	231105707	871109	165
23	7.5	8.6	F	2200	231105707R	871109	166
23	12.3	13.2	B	300	231105712	871109	167
24	1.5	2.5		5500	241105701	871109	152
24	1.5	2.5	F	1100	241105701R	871109	153
24	7.5	8.5		3200	241105707	871109	154
24	10.8	11.3	B	1700	241105710	871109	155
24	11.3	12.0	B	100	241105711	871109	156
25	1.5	2.5		700	251105701	871109	168
25	7.5	8.5		400	251105707	871109	169
25	12.2	12.7	B	<100	251105712	871109	170



TABLE A-6. PRE-VENTING HYDROCARBON ANALYSES: BENEATH FUEL TANKS  
(CONCLUDED)

Borehole	Depth BLS (ft)*		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type**	(mg/kg)	Samp No.	Date	No.
26	1.5	2.5		200	261105701	871109	157
26	7.7	8.5		2900	261105707	871109	158
26	12.8	13.6	B	600	261105712	871109	159
27	1.5	2.5		400	271105701	871109	160
27	7.8	8.5		1800	271105707	871109	161
28	1.5	2.6		1700	281106701	871109	171
28	1.5	2.6	F	2000	281106701R	871109	172
28	7.4	8.2		<100	281106707	871109	173
28	12.2	12.7	B	<100	281106712	871109	174
29	1.5	2.5		<100	291106701	871109	175
29	7.4	8.5		<100	291106707	871109	176
29	12.0	12.8	B	<100	291106712	871109	177
30	1.5	2.5		1000	301105701	871109	149
30	7.5	8.5		100	301105707	871109	150
30	12.2	13.0	B	<100	301105712	871109	151
			TB	<100	001104700	871109	114
			TB	<100	001105700	871109	148
			TB	<100	001106700	871109	163
*Measured from floor of tank excavation.							
**B=Biased sample; F=field replicate; TB=trip blank.							

TABLE A-7. PRE-VENTING HYDROCARBON ANALYSES: INITIAL EXPLORATORY BORINGS IN VERTICAL VENT AREA

Borehole No.	Depth Top	BLS (ft) Btm	Samp. Type	Total HC (mg/kg)	GJ Samp No.	ACD Samp No. Date	No.
31	1.0	2.5		<100	311218701	871223	025
31	5.0	6.5		290	311218705	871223	026
31	10.0	11.5		900	311218710	871223	027
31	15.0	16.5		<100	311218715	871223	028
31	20.0	21.5		<100	311218720	871223	029
31	25.0	26.5		<100	311218725	871223	030
31	30.0	31.5		<100	311218730	871223	031
31	35.0	36.5		<100	311218735	871223	032
31	40.0	41.5		<100	311218740	871223	033
31	45.0	46.5		<100	311218745	871223	034
31	50.0	51.5		<100	311218750	871223	035
41	1.0	2.5		1100	411219701	871223	038
41	1.0	2.5	F	2300	411219701R	871223	039
41	5.0	6.5		200	411219705	871223	040
41	10.0	11.5		1100	411219710	871223	041
41	15.0	16.5		<100	411219715	871223	042
41	20.0	21.5		<100	411219720	871223	043
41	25.0	26.5		<100	411219725	871223	044
41	30.0	31.5		600	411219730	871223	045
41	35.0	36.5		<100	411219735	871223	046
41	40.0	41.5		<100	411219740	871223	047
41	45.0	46.5		<100	411219745	871223	048
41	50.0	51.5		<100	411219750	871223	049
41	50.0	51.5	F	<100	411219750R	871223	050
42	6.0	6.5		655	4001	880608	114
42	16.0	16.5		<20	4003	880608	113
42	51.0	51.5		<20	4018	880610	046
42	52.8	53.1	B	<20	4025	880610	050
42	56.0	56.5		<20	4020	880610	047
42	61.0	61.5		<20	4022	880610	048
42	64.1	64.3	B	<20	4026	880610	051
42	66.0	66.5		<20	4024	880610	049
43	6.0	6.5		460	4029	880610	053
43	16.0	16.5		1780	4032	880610	055
43	51.0	51.5		<20	4046	880610	062
43	56.0	56.5		<20	4048	880610	063
43	66.0	66.5		<20	4053	880610	066
43	71.0	71.5		<20	4055	880610	067
43	73.0	73.5	P	<20	4056	880610	068
43	76.0	76.5		<20	4058	880610	069
43	81.0	81.5		<20	4060	880610	070
43	82.5	83.0	B	<20	4061	880610	071
43	86.0	86.5		<20	4063	880610	072
43	90.0	90.5		<20	4065	880610	073
44	6.0	6.5		545	4067	880613	195
44	51.0	51.5		<20	4083	880613	203

TABLE A-7. PRE-VENTING HYDROCARBON ANALYSES: INITIAL EXPLORATORY  
BORINGS IN VERTICAL VENT AREA  
(CONCLUDED)

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type**	(mg/kg)	Samp No.	Date	No.
44	53.7	54.2	B	<20	4084	880613	204
44	58.2	58.7	B	<20	4087	880613	206
44	61.0	61.5		<20	4090	880613	207
44	66.0	66.5		<20	4092	880613	208
44	71.0	71.5	B	<20	4094	880613	209
44	72.0	72.5		<20	4096	880613	211
44	76.0	76.5		<20	4098	880613	212
44	81.0	81.5		<20	4100	880613	213
44	86.0	86.5		<20	4102	880613	214
			TB	<100	011219700	871223	036
			TB	<100	021219700	871223	037
			TS	<20	4027	880610	052
			TS	<20	4095	880613	210

\*\*B=Biased sample; F=field replicate; TS=trip blank.

TABLE A-8. PRE-VENTING HYDROCARBON ANALYSES:  
VERTICAL VENT BORINGS

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type*	(mg/kg)	Samp No.	Date	No.
V1	1.5	3.0		<20	4130	880818	146
V1	4.5	6.0		<20	4132	880818	147
V1	7.5	9.0		<20	4134	880818	148
V1	10.5	12.0		<20	4136	880818	149
V1	10.5	12.0	F	<20	4138	880818	150
V1	13.5	15.0		<20	4140	880818	151
V1	13.5	15.0	L	<20	4140	880818	151
V1	18.5	20.0		(<20)**	4143		
V1	23.5	25.0		(<20)	4145		
V1	28.5	30.0		(<20)	4147		
V1	33.5	35.0		(<20)	4149		
V1	38.5	40.0		(<20)	4151		
V1	43.5	45.0		(<20)	4153		
V1	48.5	50.0		<20	4155	880318	158
V2	1.5	3.0		<20	4104	880817	079
V2	4.5	6.0		320	4106	880817	079
V2	7.5	9.0		1400	4108	880817	080
V2	10.5	12.0		1800	4110	880817	081
V2	13.5	15.0		2300	4112	880817	082
V2	18.5	20.0		600	4114	880817	083
V2	23.5	25.0		5700	4116	880817	084
V2	23.5	25.0	F	70	4118	880817	085
V2	28.5	30.0		<20	4120	880817	086
V2	33.5	35.0		90	4122	880817	087
V2	38.5	40.0		<20	4124	880817	088
V2	43.5	45.0		<20	4125	880817	089
V2	45.0	45.5	B	<20	4127	880817	090
V2	48.5	50.0		<20	4128	880817	091
V3	1.5	3.0		<20	4157	880823	047
V3	4.5	6.0		<20	4159	880823	048
V3	7.5	9.0		<20	4161	880823	049
V3	10.5	12.0		<20	4163	880823	050
V3	13.5	15.0		<20	4166	880823	051
V3	13.5	15.0	F	10	4167	880823	052
V3	18.5	20.0		(<20)	4169		
V3	23.5	25.0		780	4171	880823	054
V3	28.5	30.0		710	4173	880823	055
V3	28.5	30.0	L	940	4173	880823	055
V3	33.5	35.0		770	4175	880823	056
V3	37.5	38.0	B	4200	4176	880823	057
V3	38.5	40.0		640	4178	880823	058
V3	43.5	45.0		(<20)	4180		
V3	48.5	50.0		<20	4182	880823	060
V4	1.5	3.0		1400	4184	880823	061
V4	4.5	6.0		660	4186	880823	062

TABLE A-8. PRE-VENTING HYDROCARBON ANALYSES:  
VERTICAL VENT BORINGS  
(CONTINUED)

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Botm	Type*	(mg/kg)	Samp No.	Date	No.
V4	7.5	9.0		910	4189	880823	063
V4	10.5	12.0		1400	4191	880823	064
V4	13.5	15.0		580	4193	880823	065
V4	13.5	15.0	L	1100	4193	880823	065
V4	17.5	18.0	B	2900	4196	880823	067
V4	18.5	20.0		450	4195	880823	066
V4	18.5	20.0	F	1540	4197	880823	068
V4	18.5	20.0	L	1600	4197	880823	068
V4	23.5	25.0		<20	4199	880823	077
V4	28.5	30.0		<20	4201	880823	078
V4	33.5	35.0		<20	4203	880823	079
V4	38.5	40.0		<20	4205	880823	080
V4	43.5	45.0		<20	4207	880823	081
V5	1.5	3.0		<20	4393	880901	060
V5	4.5	6.0		<20	4396	880901	061
V5	4.5	6.0	F	<20	4397	880901	062
V5	7.5	9.0		<20	4399	880901	063
V5	10.5	12.0		<20	4401	880901	064
V5	12.8	13.0	B	<20	4408	880901	068
V5	13.5	15.0		<20	4403	880901	065
V5	18.5	20.0		(<20)	4405		
V5	23.5	25.0		(<20)	4407		
V5	28.5	30.0		(<20)	4410		
V5	33.5	35.0		<20	4412	880901	070
V5	38.5	40.0		(<20)	4414		
V5	43.5	45.0		<20	4416	880901	072
V5	48.5	50.0		<20	4418	880901	073
V6	1.5	3.0		<20	4367	880831	132
V6	4.5	6.0		<20	4369	880831	133
V6	7.5	9.0		<20	4371	880831	134
V6	10.5	12.0		<20	4373	880831	135
V6	13.5	15.0		<20	4375	880831	136
V6	13.5	15.0	F	<20	4377	880831	137
V6	18.5	20.0		<20	4379	880831	138
V6	18.5	20.0	L	<20	4379	880831	138
V6	23.5	25.0		<20	4381	880831	139
V6	28.5	30.0		<20	4383	880831	140
V6	33.5	35.0		<20	4385	880831	141
V6	33.5	40.0		<20	4387	880831	142
V6	43.5	45.0		4000	4399	880831	143
V6	48.5	50.0		2700	4391	880831	144
V6	48.5	50.0	L	3000	4391	880831	144
V8	1.5	3.0		360	4257	880824	063
V8	7.5	3.0	L	400	4257	880824	063
V8	4.5	6.0		35	4259	880824	064

TABLE A-8. PRE-VENTING HYDROCARBON ANALYSES:  
VERTICAL VENT BORINGS  
(CONTINUED)

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Bottom	Type*	(mg/kg)	Samp No.	Date	No.
V8	7.5	9.0		<20	4261	880824	065
V8	10.5	12.0		<20	4263	880824	066
V8	13.5	15.0		<20	4265	880824	067
V8	18.5	20.0		<20	4268		
V8	23.5	25.0		<20	4270	880824	070
V8	23.5	25.0	L	<20	4270	880824	070
V8	27.0	27.5	B	680	4273	880824	072
V8	28.5	30.0		<20	4272		
V8	28.5	30.0	F		4274		
V8	33.5	35.0		<20	4276		
V8	38.5	40.0		560	4278	880824	075
V8	43.5	45.0		<20	4280	880824	076
V8	46.5	47.0	B	5300	4283	880824	078
V8	48.5	50.0		<20	4282		
V9	1.5	3.0		2900	4523	880915	059
V9	4.5	6.0		2300	4526	880915	060
V9	4.5	6.0	F	2300	4527	880915	061
V9	7.5	9.0		390	4529	880915	062
V9	10.5	12.0		360	4531	880915	063
V9	13.5	15.0		<20	4533	880915	071
V9	18.5	20.0		5300	4535	880915	064
V9	18.5	20.0	L	6300	4535	880915	064
V9	23.5	25.0		<20	4537	880915	065
V9	28.5	30.0		2800	4539	880915	066
V9	33.5	35.0		650	4541	880915	067
V9	38.5	40.0		210	4543	880915	068
V9	43.5	45.0		<20	4545	880915	069
V9	48.5	50.0		<20	4547	880915	070
V10	7.5	9.0		1000	4499	880913	266
V10	7.5	9.0	L	1100	4499	880913	266
V10	10.5	12.0		2400	4501	880913	267
V10	13.5	15.0		20400	4504	880913	268
V10	13.5	15.0	L	8600	4504	880913	268
V10	13.5	15.0	F	1400	4505	880913	269
V10	18.5	20.0		2400	4507	880913	270
V10	23.5	25.0		2400	4509	880913	271
V10	28.5	30.0		<20	4511	880913	272
V10	33.5	35.0		<20	4513	880913	273
V10	38.5	39.0	B	6300	4514	880913	277
V10	38.5	39.0	L.B	6400	4514	880913	277
V10	39.0	40.0		40	4516	880913	274
V10	43.5	45.0		40	4518	880913	275
V10	48.5	50.0		<20	4520	880913	276
V11	1.5	3.0		1900	4209	880823	082
V11	4.5	6.0		<20	4211	880823	083

TABLE A-8. PRE-VENTING HYDROCARBON ANALYSES:  
VERTICAL VENT BORINGS  
(CONTINUED)

Borehole	Depth BLS (ft)		Samp.	Total HC	GU	ACD Samp No.	
No.	Top	Botm	Type*	(mg/kg)	Samp No.	Date	No.
V11	7.5	9.0		<20	4213	880823	084
V11	10.5	12.0		307	4215	880823	085
V11	13.5	15.0		<20	4218	880823	086
V11	18.5	20.0		<20	4220	880823	087
V11	23.5	25.0		<20	4222		
V11	25.5	30.0		<20	4224	880823	089
V11	35.5	36.0	B	10200	4225	880823	097
V11	38.5	40.0		<20	4227		
V11	38.5	40.0	F	<20	4228		
V11	43.5	45.0		<20	4230		
V12	1.5	3.0		<20	4285	880824	079
V12	4.5	6.0		<20	4287	880824	080
V12	7.5	9.0		<20	4289	880824	081
V12	10.5	12.0		<20	4291	880824	082
V12	13.5	15.0		<20	4293	880824	083
V12	18.5	20.0		<20	4295		
V12	23.5	25.0		<20	4297		
V12	28.5	30.0		<20	4300		
V12	33.5	35.0		<20	4302		
V12	38.5	40.0		<20	4304		
V12	38.5	40.0	F	<20	4305		
V12	43.5	45.0		<20	4307		
V12	47.0	47.5	B	<20	4310	880824	093
V12	48.5	50.0		<20	4309		
V13	1.5	3.0		<20	4312	880826	079
V13	4.5	6.0		<20	4314	880826	080
V13	7.5	9.0		<20	4316	880826	081
V13	10.5	12.0		<20	4318	880826	082
V13	12.5	13.0	B	<20	4320	880826	083
V13	13.5	15.0		<20	4322	880826	084
V13	18.5	20.0		<20	4324		
V13	23.5	25.0		<20	4326		
V13	27.0	27.5	B	<20	4329	880826	088
V13	28.5	30.0		<20	4328		
V13	32.0	32.5	B	<20	4332	880826	090
V13	33.5	35.0		<20	4331		
V13	33.5	34.0	B	<20	4333	880826	091
V13	38.5	40.0		<20	4335		
V13	43.5	45.0		<20	4337		
V14	1.5	3.0		<20	4340	880826	094
V14	4.5	6.0		<20	4342	880826	095
V14	7.5	9.0		<20	4344	880826	096
V14	10.5	12.0		<20	4346	880826	097
V14	13.5	15.0		<20	4349	880826	098
V14	13.5	15.0	F	<20	4350	880826	099

TABLE A-8. PRE-VENTING HYDROCARBON ANALYSES:  
VERTICAL VENT BORINGS  
(CONCLUDED)

Borehole	Depth SLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type*	(mg/kg)	Samp No.	Date	No.
V14	18.5	20.0		<20	4352		
V14	23.5	25.0			4354		
V14	28.5	30.0		<20	4356		
V14	33.5	35.0		<20	4358		
V14	38.5	40.0		400	4360	880826	104
V14	43.5	45.0		<20	4362		
V14	48.5	50.0		<20	4364		
V15	7.5	9.0		<20	4232	880823	093
V15	10.0	10.5	B	45	4238	880823	096
V15	10.5	12.0		900	4234	880823	094
V15	10.5	12.0	L	510	4234	880823	094
V15	13.5	15.0		<20	4237	880823	095
V15	18.5	20.0		<20	4240	880823	098
V15	23.5	25.0		<20	4242		
V15	28.5	30.0		<20	4244		
V15	28.5	30.0	F	<20	4245		
V15	32.0	32.5	B	<20	4246	880823	101
V15	33.5	35.0		<20	4248	880823	102
V15	37.5	38.0	B	<20	4249	880823	103
V15	38.5	40.0		<20	4251		
V15	43.5	45.0		<20	4253		
V15	48.5	50.0		<20	4255		
E	1.5	3.0		40	4461	880909	164
E	4.5	6.0		770	4463	880909	165
E	7.5	9.0		1100	4465	880909	166
E	10.5	12.0		1500	4467	880909	167
E	13.5	15.0		1500	4469	880909	168
E	13.5	15.0	F	3900	4470	880909	169
E	18.5	20.0		1500	4472	880909	170
E	18.5	20.0	L	1900	4472	880909	170
E	23.5	25.0		2300	4474	880909	171
E	28.5	30.0		1200	4477	880909	172
E	33.5	35.0		<20	4479	880909	173
E	38.5	40.0		<20	4481	880909	174
E	43.5	45.0		<20	4483	880909	175
E	48.5	50.0		<20	4485	880909	176
E	53.5	55.0		<20	4487	880909	177
E	57.2	57.5	B	<20	4490	880909	179
E	58.5	60.0		<20	4489	880909	178
E	62.0	62.2	B	<20	4493	880909	180
Y	1.5	3.0		<20	4422	880906	069
Y	4.5	6.0		<20	4424	880906	070
Y	4.5	6.0	F	<20	4425	880906	071
Y	7.5	9.0		<20	4428	880906	072
Y	10.5	12.0		<20	4430	880906	073



TABLE A-9. PRE-VENTING HYDROCARBON ANALYSES: PILE

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type*	(mg/kg)	Samp No.	Date	No.
P1	1	2		<10	4562	881111	037
P1	3.2	4.2		<10	4563	881111	038
P1	6.4	7.4		1400	4564	881111	039
P2	1	2		180	4558	881111	033
P2	3.2	4.2		230	4559	881111	034
P2	4.2	5.2		920	4560	881111	035
P2	6.2	7.2		1000	4561	881111	036
P3	1	2		45	4565	881111	040
P3	3	4		1400	4566	881111	041
P3	4.5	5.5		3250	4567	881111	042
P4	1	2		40	4548	881111	023
P4	3	4		780	4549	881111	024
P4	6.5	7.5		70	4550	881111	025
P5	1	2		1160	4551	881111	026
P5	3	4		2100	4552	881111	027
P5	4.3	5.3		740	4553	881111	028
P5	6.2	7.2		70	4554	881111	029
P5	1	2		40	4555	881111	030
P6	3	4		470	4556	881111	031
P6	4.6	5.6		3450	4557	881111	032
P7	1	2		<10	4569	881111	044
P7	3.2	4.2		10	4570	881111	045
P7	6.6	7.6		30	4571	881111	046
P8	1	2		10	4572	881111	047
P8	3	4		38	4573	881111	048
P8	4	5		40	4574	881111	049
P8	5.3	6.3		65	4575	881111	050
P9	1	2		<10	4576	881111	051
P9	3.3	4.3		35	4577	881111	052
P9	4.5	5.5		40	4578	881111	053
P10	1	2		<10	4579	881111	054
P10	3.3	4.3		10	4580	881111	055
P10	6.6	7.6		10	4581	881111	056
P11	1	2		10	4582	881111	057
P11	3	4		10	4583	881111	058
P11	5.1	6.1		10	4584	881111	059
P12	1	2		10	4585	881111	060
P12	3.2	4.2		50	4586	881111	061
P12	4.6	5.6		45	4587	881111	062
			TB	<10	4568	881111	043
*TB=Trip blank							

TABLE A-10. CONCENTRATIONS OF BENZENE, TOLUENE, AND XYLENES IN SOIL SAMPLES COLLECTED DURING PRE-VENTING CHARACTERIZATION OF VERTICAL VENTED AREA

GJ No.	ACID No. (891222)	Vent No.	Depth (ft)	Total H/C (mg/kg)	Concentration (mg/kg)			Fraction of Total (%)
					Benzene	Toluene	Xylene	
4116	083	V2	23.5-25	5700	<20	120	420	9.5
4173	08	V3	28.5-30	940	<20	<20	<20	<2.1
4195	085	V4	18.5-20	450	<20	92	<20	20.4
4225	086	V11	35.5-36	10200	<20	<20	<20	0.2
4283	087	V8	46.5-47	5400	<20	158	152	5.2
4391	088	V6	48.5-50	2850	<20	194	294	17.1
4504	089	V10	13.5-15	14600	<20	136	208	3.0
4514	090	V10	38.5-39	6350	<20	308	534	13.3
4535	091	V9	18.5-20	5300	<20	<20	596	11.2
4535R	092	V9	18.5-20	6300	<20	<20	600	9.5

TABLE A-11. HYDROCARBON CONCENTRATIONS: EXCAVATION BOREHOLES

Borehole No.	Depth Below Surface (ft)	Repl	n-Paraffin Hydrocarbons (ppg)										Detection Limit: 0.2 µg/g				Corr.				C-17																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
			C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17	C-18	C-19	C-20																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
1	15	35																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																

TABLE A-11. HYDROCARBON CONCENTRATIONS: EXCAVATION BOREHOLES  
(CONTINUED)

Borehole ID	Depth Below Surface (ft)		Rqd	C-6		C-7		Aromatic Hydrocarbons		(µg)		Detection Limit		C-14		C-15		C-16		C-17		Corr.
	Top	Bot		C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17	C-18	C-19	C-20	C-21	C-22	C-23	C-24		
23	15	25																				
25	15	25																				
25	75	95																				
5	122	127																				
23	15	25																				
23	77	85																				
26	123	136																				
27	15	25																				
27	70	85																				
28	15	25																				
28	15	25																				
28	74	82																				
28	122	127																				
29	15	25																				
29	74	85																				
30	129	138																				
30	15	25																				
30	75	85																				
30	123	130																				

Corrected for Extraction Blank

\* Based on corrected values for C-16 and C-17

TABLE A-11. HYDROCARBON CONCENTRATIONS: EXCAVATION BOREHOLES  
(CONTINUED)

TABLE A-11. HYDROCARBON CONCENTRATIONS: EXCAVATION BOREHOLES  
(CONCLUDED)

Borehole No.	Depth Below Surface (ft)	Component Fraction of Total Purified Hydrocarbons															
		C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17	C-18	C-19	C-20	C-21
25	15	0.0	0.0	0.0131	0.1235	0.2832	0.2324	0.1017	0.0890	0.0550	0.0327	0.0433	0.0116				
25	75	0.0	0.0	0.0155	0.0787	0.1663	0.2217	0.1220	0.1108	0.0732	0.0632	0.0772	0.020				
25	127	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
26	15	0.0	0.0	0.0	0.0	0.0574	0.2670	0.2003	0.1736	0.1148	0.0981	0.0249	0.0010				
26	77	0.0	0.0051	0.0784	0.2516	0.3202	0.2252	0.0718	0.0550	0.0153	0.0120	0.0040	0.0010				
26	129	0.0	0.0642	0.2458	0.2937	0.1839	0.1228	0.0512	0.0312	0.0464	0.0225	0.0332	0.0184				
27	15	0.0	0.0	0.0	0.0	0.1081	0.2348	0.1894	0.1870	0.1384	0.0833	0.0157	0.0023				
27	78	0.0	0.0	0.0010	0.0617	0.2217	0.2830	0.1509	0.1038	0.0637	0.0813	0.0353	0.0038				
28	15	0.0	0.0088	0.0528	0.1944	0.2832	0.2348	0.0872	0.0528	0.0206	0.0254	0.0082	0.0021				
28	74	0.0	0.0121	0.0638	0.2375	0.2924	0.1861	0.0815	0.0443	0.0284	0.0284	0.0141	0.0034				
28	122	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0813	0.0488				
28	15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1983	0.050				
28	74	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0136	0.0408				
28	120	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1759	0.111				
29	15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
29	74	0.0	0.0	0.0123	0.0890	0.2739	0.2817	0.1308	0.0840	0.0613	0.0450	0.0101	0.0020				
29	124	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
30	15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
30	74	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
30	124	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				

TABLE A-12. HYDROCARBON CONCENTRATIONS: BOREHOLES 31 AND 41

Borehole No.	Depth Below Surface		Repl.	C-6		C-7		n-Paraffin Hydrocarbons (µg/g)		Detection Limit: 0.2 µg/g		C-15		C-16		C-17	
	Top	Bottom		C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17	Corr.	Corr.
31	10	2.5															
31	5	6.5															
31	10	11.5															
31	15	16.5															
31	20	21.5															
31	25	26.5															
31	30	31.5															
31	35	36.5															
31	40	41.5															
31	45	46.5															
31	50	51.5															
41	1	2.5															
41	1	2.5															
41	5	6.5															
41	10	11.5															
41	15	16.5															
41	20	21.5															
41	25	26.5															
41	30	31.5															
41	35	36.5															
41	40	41.5															
41	45	46.5															
41	50	51.5															
41	55	56.5															
41	60	61.5															
41	65	66.5															
41	70	71.5															
41	75	76.5															
41	80	81.5															
41	85	86.5															
41	90	91.5															
41	95	96.5															
41	100	101.5															
41	105	106.5															
41	110	111.5															
41	115	116.5															
41	120	121.5															
41	125	126.5															
41	130	131.5															
41	135	136.5															
41	140	141.5															
41	145	146.5															
41	150	151.5															
41	155	156.5															
41	160	161.5															
41	165	166.5															
41	170	171.5															
41	175	176.5															
41	180	181.5															
41	185	186.5															
41	190	191.5															
41	195	196.5															
41	200	201.5															
41	205	206.5															
41	210	211.5															
41	215	216.5															
41	220	221.5															
41	225	226.5															
41	230	231.5															
41	235	236.5															
41	240	241.5															
41	245	246.5															
41	250	251.5															
41	255	256.5															
41	260	261.5															
41	265	266.5															
41	270	271.5															
41	275	276.5															
41	280	281.5															
41	285	286.5															
41	290	291.5															
41	295	296.5															
41	300	301.5															
41	305	306.5															
41	310	311.5															
41	315	316.5															
41	320	321.5															
41	325	326.5															
41	330	331.5															
41	335	336.5															
41	340	341.5															
41	345	346.5															
41	350	351.5															
41	355	356.5															
41	360	361.5															
41	365	366.5															
41	370	371.5															
41	375	376.5															
41	380	381.5															
41	385	386.5															
41	390	391.5															
41	395	396.5															
41	400	401.5															
41	405	406.5															
41	410	411.5															
41	415	416.5															
41	420	421.5															
41	425	426.5															
41	430	431.5															
41	435	436.5															
41	440	441.5															
41	445	446.5															
41	450	451.5															
41	455	456.5															
41	460	461.5															
41	465	466.5															
41	470	471.5															
41	475	476.5															
41	480	481.5															
41	485	486.5															
41	490	491.5															
41	495	496.5															
41	500	501.5															
41	505	506.5															
41	510	511.5															
41	515	516.5															
41	520	521.5															
41	525	526.5															
41	530	531.5															
41	535	536.5															
41	540	541.5															
41	545	546.5															
41	550	551.5															
41	555	556.5															
41	560	561.5															
41	565	566.5															
41	570	571.5															
41	575	576.5															
41	580	581.5															
41	585	586.5															
41	590	591.5															
41	595	596.5															

TABLE A-12. HYDROCARBON CONCENTRATIONS: BOREHOLES 31 AND 41  
(CONCLUDED)

Borehole No.	Depth Below Surf (ft)		Component Fraction of Total Paraffinic Hydrocarbons															Corr.	
	Top	Bottom	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17		
31	10	25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2222	0.0	0.7222	0.0556		
31	5	9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3260	0.2810	0.0882	0.0221	0.0147	0.0	0.1642	0.0098		
31	10	11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1815	0.3050	0.2531	0.0880	0.0303	0.0177	0.0	0.0212	0.0014		
31	15	16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3839	0.3001	0.3030	0.0	0.0	0.0	0.3030	0.0		
31	20	21.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
31	25	26.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0		
31	30	31.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0		
31	35	36.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9333	0.0667		
31	40	41.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9375	0.0625		
31	45	46.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9412	0.0588		
31	50	51.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8524	0.1476		
End Blank																0.9375	0.0625		
Top Blank																			
Top Blank																			
41	1	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
41	1	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
41	1	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2639	0.2644	0.0955	0.0468	0.0404	0.0	0.0	0.0		
41	10	11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.2111	0.3884	0.3206	0.0727	0.0210	0.0211	0.0	0.0	0.0		
41	15	16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1326	0.3078	0.210	0.0276	0.0134	0.0135	0.0	0.0	0.0		
41	20	21.5	0.0	0.0	0.0	0.0	0.0	0.0	0.191	0.3408	0.2551	0.0768	0.0329	0.0107	0.0	0.0	0.0		
41	25	26.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
41	30	31.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
41	35	36.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
41	40	41.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
41	45	46.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
41	50	51.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
41	50	51.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
End Blank																0.0676	0.0		
																0.1724	0.0245		



TABLE A-13. JP-4 HYDROCARBON MASS PRESENT BENEATH THE EXCAVATED FUEL TANKS BEFORE VENTING

Borehole No.	Depth BLS (ft)		Water Content (1)	JP-4 Conc. (mg/kg)		Dry Wt (2)	Cell Dimensions (ft)		
	Top	Bottom		Measured	Nominal		Thickness (3)	E-W	N-S
1	1.5	3.5	0.09	100	100	109	3.5	18	18
1	8.5	10.5	0.09	100	100	109	7	18	18
1	13.5	14.1	0.27	1000	1000	1270	3.6	18	18
3	1.5	2.5	0.03	<100	50	55	2.5	11	18
3	7.5	8.5	0.09	<100	50	55	6	11	18
3	12.8	13.3	0.27	<100	50	64	4.8	11	18
5	1.5	2.5	0.09	2400	2400	2616	2.5	23	18
5	7.5	8.5	0.09	1500	1500	1635	6	23	10
5	12.5	13.0	0.27	200	200	254	4.5	23	18
12	1.5	2.5	0.09	2450	2450	2671	2.5	20	16
12	7.5	8.5	0.09	3200	3200	3488	6	20	18
12	12.6	13.2	0.27	300	300	381	4.7	20	18
16	0.0	1.0	0.09	1400	1400	1526	1	18	10
16	1.0	2.0	0.09	2500	2500	2725	1	18	18
16	2.0	3.0	0.09	6500	6500	7085	1	18	18
16	3.0	4.0	0.09	5000	5000	5450	1	18	18
16	4.0	5.0	0.09	5400	5400	5886	1	18	18
16	5.0	6.0	0.09	6400	6400	6976	1	18	18
16	6.0	7.0	0.09	4700	4700	5123	1	18	18
16	7.0	8.0	0.09	3800	3800	4142	1	18	18
16	8.0	9.0	0.09	1100	1100	1199	1	18	18
16	9.0	10.0	0.09	200	200	218	1	18	18
16	10.0	11.0	0.27	1100	1100	1397	1	18	18
16	11.0	12.0	0.27	350	350	445	1	18	18
16	12.0	13.0	0.27	100	100	127	1	18	18
16	13.0	14.0	0.27	600	600	762	1	18	18
16	14.0	15.0	0.27	600	600	762	1	18	18
16	15.0	16.0	0.27	400	400	508	1	18	18
16	16.0	17.0	0.27	800	800	1016	1	18	18
18	1.5	2.7	0.09	100	100	109	2.7	14	18
18	7.5	8.2	0.09	5000	5000	5450	5.5	14	18

TABLE A-13. JP-4 HYDROCARBON MASS PRESENT BENEATH THE EXCAVATED FUEL TANKS BEFORE VENTING  
(CONTINUED)

Borehole No.	Depth BLS (ft)		Water Content (1)	JP-4 Conc. (mg/kg)		Dry Wt (2)	Cell Dimensions (ft)		
	Top	Bottom		Measured	Nominal		Thickness (3)	E-W	N-S
18	12.5	13.0	0.27	200	200	254	4.8	14	18
23	2.5	3.5	0.09	900	900	981	3.5	20	19
23	7.5	8.6	0.09	2150	2150	2344	5.1	20	18
23	12.3	13.2	0.27	300	300	381	4.6	20	18
24	1.5	2.5	0.09	3300	3300	3597	2.5	18	18
24	7.5	8.5	0.09	3200	3200	3488	6	12	18
24	10.8	11.3	0.27	1700	1700	2159	2.0	18	18
24	11.3	12.0	0.27	100	100	127	0.7	18	18
25	1.5	2.5	0.09	700	700	763	2.5	20	18
25	7.5	8.5	0.09	400	400	436	6	20	18
25	12.2	12.7	0.27	<100	50	64	4.2	20	18
26	1.5	2.5	0.09	200	200	219	2.5	14	16
26	7.7	8.5	0.09	2900	2900	3161	6	14	18
26	12.8	13.6	0.27	600	600	762	5.1	14	10
27	1.5	2.5	0.09	400	400	436	2.5	18	18
27	7.8	8.5	0.09	1600	1800	1962	6	18	18
28	1.5	2.6	0.09	1850	1850	2017	2.6	20	18
28	7.4	8.2	0.09	<100	50	55	5.6	20	18
28	12.2	12.7	0.27	<100	50	64	4.5	20	18
29	1.5	2.5	0.09	<100	50	55	2.5	14	18
29	7.4	8.5	0.09	<100	50	55	6	14	18
29	12.0	12.8	0.27	<100	50	64	4.3	14	16
30	1.5	2.5	0.09	1000	1000	1090	2.5	18	18
30	7.5	8.5	0.09	100	100	109	6	18	18
30	12.2	13.0	0.27	<100	50	64	4.5	18	18

TABLE A-13. JP-4 HYDROCARBON MASS PRESENT BENEATH THE EXCAVATED FUEL TANKS BEFORE VENTING  
(CONTINUED)

Borehole No.	Depth BLS (ft)		Water Content (1)	JP-4 Conc. (mg/kg)		Dry Wt (2)	Cell Dimensions (ft)		
	Top	Bottom		Measured	Nominal		Thickness (3)	E-W	N-S
(1) Mean of samples from 4 borings: 0.09 above 10 ft depth; 0.27 below 10 ft depth									
(2) Nominal conc. x (1) Mean water content									
(3) Bottom of sampled interval considered as lower boundary of soil interval									
(4) Thickness x (E-W dimension) x (N-S dimension)									
(5) (4) x 28.32 L/m <sup>3</sup>									
(6) (5) x 1.67 g/cm <sup>3</sup>									
(7) (6) x (6)/100000									
(8) Sum of all cells per borehole area.									
(9) (8)/Total fuel mass									

TABLE A-13. JP-4 HYDROCARBON MASS PRESENT BENEATH THE EXCAVATED FUEL TANKS BEFORE VENTING  
(CONTINUED)

Borehole No	Depth BLS (ft)		Volume (ft <sup>3</sup> )	Soil Volume (L)	Soil Mass (kg)	Initial Fuel Mass (kg)	Fuel Mass per Area (kg)	Fraction of Total (%)
	Top	Bottom	(4)	(5)	(6)	(7)	(8)	(9)
1	1.5	3.5	1134	32115	53632	5.85		
1	8.5	10.5	2268	64230	107264	11.69		
1	13.5	14.1	1166	33032	55164	70.06	87.60	2.45
3	1.5	2.5	495	14018	23411	1.28		
3	7.5	8.5	1188	33644	56186	3.06		
3	12.8	13.3	950	26915	44949	2.85	7.19	0.20
5	1.5	2.5	1035	29311	40950	128.05		
5	7.5	8.5	2484	70347	117479	192.08		
5	12.5	13.0	1863	52760	88103	22.36	342.51	9.58
12	1.5	2.5	900	25488	42565	113.67		
12	7.5	8.5	2160	61171	102156	356.32		
12	12.6	13.2	1692	47917	80022	30.49	500.48	14.00
16	0.0	1.0	324	9176	15323	23.38		
16	1.0	2.0	324	9176	15323	41.76		
16	2.0	3.0	324	9176	15323	108.57		
16	3.0	4.0	324	9176	15323	83.51		
16	4.0	5.0	324	9176	15323	90.19		
16	5.0	6.0	324	9176	15323	106.90		
16	6.0	7.0	324	9176	15323	79.50		
16	7.0	8.0	324	9176	15323	63.47		
16	8.0	9.0	324	9176	15323	16.37		
16	9.0	10.0	324	9176	15323	3.34		
16	10.0	11.0	324	9176	15323	21.41		
16	11.0	12.0	324	9176	15323	6.81		
16	12.0	13.0	324	9176	15323	1.95		
16	13.0	14.0	324	9176	15323	11.68		
16	14.0	15.0	324	9176	15323	11.68		
16	15.0	16.0	324	9176	15323	7.78		
16	16.0	17.0	324	9176	15323	15.57	694.86	19.44
18	1.5	2.7	680	19269	32179	3.51		
18	7.5	8.2	1386	39252	65550	357.25		

TABLE A-13. JP-4 HYDROCARBON MASS PRESENT BENEATH THE EXCAVATED FUEL TANKS BEFORE VENTING  
(CONCLUDED)

Borehole No.	Depth NLS (ft)		Volume (ft <sup>3</sup> )	Soil Volume (L)	Soil Mass (kg)	Initial Fuel Mass (kg)	Fuel Mass per Area (kg)	Fraction of Total (%)
	Top	Bottom						
18	12.5	13.0	1210	34256	57207	14.53	375.29	10.50
23	2.5	3.5	1260	35683	59591	58.46		
23	7.5	8.6	1835	51995	86832	203.49		
23	12.3	13.2	1656	46898	78320	29.84	291.79	8.16
24	1.5	2.5	810	22939	38308	137.80		
24	7.5	8.5	1944	55054	91940	320.69		
24	10.8	11.3	907	25692	42905	92.63		
24	11.3	12.0	227	6423	10726	1.36	552.48	15.46
25	1.5	2.5	900	25488	42565	32.48		
25	7.5	8.5	2160	61171	102156	44.54		
25	12.2	12.7	1512	42820	71509	4.54	81.56	2.28
26	1.5	2.5	630	17842	29795	6.50		
26	7.7	8.5	1512	42820	71509	226.04		
26	12.8	13.6	1285	36397	60783	46.32	278.85	7.80
27	1.5	2.5	810	22939	38308	16.70		
27	7.8	8.5	1944	55054	91940	180.39	197.09	5.51
28	1.5	2.6	936	26508	44268	83.27		
28	7.4	8.2	2016	67093	95346	5.20		
28	12.2	12.7	1620	45879	76617	4.87	99.33	2.78
29	1.5	2.5	630	17842	29795	1.62		
29	7.4	8.5	1512	42820	71509	3.90		
29	12.0	12.8	1084	30568	51248	3.25	8.78	0.25
30	1.5	2.5	810	22939	38308	41.76		
30	7.5	8.5	1944	55054	91940	10.02		
30	12.2	13.0	1458	41291	68355	1.38	56.16	1.57
					Total:	3573.95 (7881 lb)		

APPENDIX B  
COORDINATES OF VENTS, PRESSURE MONITORING POINTS, AND NEUTRON  
ACCESS TUBES

TABLE B-1. COORDINATES OF VENTS, PRESSURE MONITORING POINTS, AND  
NEUTRON ACCESS TUBES  
(ALL VALUES IN FEET)

VERTICAL VENTS

VENT	E/W	N/S
V1	14.6	109.9
V2	54.8	109.4
V3	89.4	108.1
V4	129.1	106.4
V5	13.2	71.9
V6	32.9	71.1
V7	53.0	70.1
V8	70.5	68.9
V9	88.2	68.1
V10	107.5	67.5
V11	127.7	66.7
V12	11.5	32.0
V13	51.6	30.2
V14	26.8	27.7
V15	127.1	28.4

PRESSURE MONITORING POINTS

VERTICAL SUBSYSTEM (CONTD)

POINT	E/W	N/S	DEPTH
B&V9	88.4	78.2	4
B&B	89.6	88.3	4
B&V3	89.0	88.2	4
CEF	104.5	84.5	4
V3&A	89.7	118.3	4
2A	90.0	128.4	4
24FV8	89.8	89.5	4
52FV8	91.3	71.1	4
72FV9	92.5	72.3	4
1FV7	51.7	66.8	4
2FV7	48.8	66.9	4
3FV7	48.9	66.0	4
4FV7	47.9	85.0	4

PRESSURE MONITORING POINTS

VERTICAL SUBSYSTEM

POINT	E/W	N/S	DEPTH
A	90.0	123.4	30
B	58.8	88.3	30
C	107.2	88.9	6
E	107.0	86.1	45
F	110.9	85.7	25
H	95.7	81.8	25
J	98.6	78.2	65
K	59.4	76.2	30
M	92.4	74.6	25
N	94.6	72.6	65
P	9.0	72.7	30
Q	94.8	68.2	30
R	84.2	60.1	30
S	45.7	63.9	6
T	44.4	65.7	55
U	37.4	59.7	9
W	40.2	55.4	25
X	30.4	50.0	6
Y	35.1	51.5	55
Z	29.9	48.1	25
AA	51.8	8.5	30
BB	84.0	7.1	30
22	47.5	62.4	15
33	35.1	46.0	45
34	44.1	72.8	30
35	24.7	70.5	15
36	34.1	64.0	30
37	54.6	80.4	45
38	54.7	90.0	30
39	42.5	80.5	45
40	58.5	88.2	15
UAW	39.8	57.6	4
XY233	32.8	48.8	4
NA1&V13	51.0	40.7	4
SS02	46.7	62.2	4
V13&A	51.7	79.4	4
MAN	93.5	73.9	4
JAH	97.8	76.0	4

PRESSURE MONITORING POINTS

LATERAL SUBSYSTEM

POINT	E/W	N/S	DEPTH
1	195	60.4	18.5
2	169.7	82	15.2
3	185.7	61.9	17.4
4	181.8	82	20.6
5	174.0	60.8	20.1
6	187.7	65.8	14.6
7	185.7	65.7	17
8	179.5	85.5	20
9	189.5	69.4	14.9
10	186	69.1	17.3
11	181.4	69.3	20.1
12	194.4	78.4	17.1
13	189.3	78.1	15.2
14	185.1	78	17.2
15	181	77.4	20.4
16	171.7	77.8	17.1
17	186.9	80.3	14.2
18	182.7	80.4	17.2
19	178.8	80.1	19.1
20	188.9	84.4	14.7
21	184.8	84.2	17.4
22	180.6	84	10.8
23	190.2	97	14.7
24	189.4	94.3	17
25	195.4	112.8	16.9
26	181.7	113.1	17.2
27	109.1	112.7	16.1
28	181	132.8	17.2
30	188.5	132	18.2
35	171.7	77.8	28.9
36	193.7	132.2	16.7

NEUTRON ACCESS TUBES

TUBE	E/W	N/S
N-1	50.4	51.1
N-2	84.8	55.0
NA3	30.2	0.0

APPENDIX C  
EXTRACTED GAS ANALYSES



TABLE C-1. SUMMARY OF GAS SAMPLING RESULTS (GC)

[illegible]

256

SUBJECT	DATE	TIME	CLASS	PT	CS	CS C6	CE C7	C7 C8	C8 C9	C9 C10	C10 C12	C12 C13	C13 C14	MC	TOTAL	AVG
0165A	09/27/99	1315	6-200000	11	0	0	402	267	515	194	219	0342	0162	0	6918	6.7652
0165B	09/27/99	1315	731-0000	11	056	103	284	768	449	194	225	029	059	015	3002	6.7299
0165C	09/27/99	1315	711-0000	10	026	0	141	363	579	1043	1132	0895	403	096	6304	6.9204
0165D	09/27/99	1311	812-0000	11	0	103	114	798	433	281	175	073	0	0	3196	6.5951
0165E	09/27/99	1304	812-0000	10	0	0	089	247	459	244	1692	048	0	0	4453	9.0931
0165F	09/27/99	1304	932-0000	11	0	085	249	2	356	294	25	0783	0	0	2269	8.84331
0165G	09/27/99	1213	932-0000	10	0	0	09	2	388	340	224	065	046	0	2988	9.0318
0165H	09/27/99	1219	1023-0000	11	0927	157	158	598	326	325	226	093	0	0	1606	8.87678
0165I	09/27/99	1219	1023-0000	11	0946	175	176	579	344	289	255	108	0	0	1472	8.87304
0165J	09/27/99	1215	1023-0000	10	0	0	0	241	32	301	286	095	0	0	2559	9.4191
0165K	09/27/99	1215	1023-0000	10	0	0	0	241	271	252	331	0588	109	0	2957	9.18265
0165L	09/27/99	1215	1023-0000	10	0	0	0	331	447	344	0116	0	0	0	1931	8.57306
0165M	09/27/99	1215	1023-0000	10	072	129	36	24	272	285	31	189	062	0	1931	8.57306
0165N	09/27/99	1215	1023-0000	10	0	142	261	534	18	202	298	051	182	0	2085	8.139
0165O	09/27/99	1215	1023-0000	10	0	0	0	161	311	312	214	023	0	0	3122	10.2434
0165P	09/27/99	1215	1023-0000	10	0	0	0	279	202	355	316	046	0	0	2373	8.8046
0165Q	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165R	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165S	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165T	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165U	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165V	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165W	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165X	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165Y	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165Z	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165A	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165B	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165C	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165D	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165E	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165F	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165G	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165H	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165I	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165J	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165K	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165L	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165M	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165N	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165O	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165P	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165Q	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165R	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165S	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165T	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165U	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165V	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165W	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165X	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165Y	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004
0165Z	09/27/99	1215	1023-0000	10	0	0	0	99	202	294	364	245	0	0	1657	9.3004

TABLE C-2. SUMMARY OF THA RESULTS

CUMUL CU FT	THA PPM	CUMUL CU FT	THA PPM	CUMUL CU FT	THA PPM	CUMUL CU FT	THA PPM	CUMUL CU FT	THA PPM	CUMUL CU FT	THA PPM
12	45372	35963	20678	163502	26399	499326	20674	577526	20022	2181623	15395
14	45372	36001	22484	166989	25909	508294	20138	886158	19224	2114178	16600
16	45372	36097	24090	171373	25904	514818	20467	891481	18408	2228053	15188
30	45372	36221	24090	175400	25464	517370	20499	898813	17987	2237501	14684
39	45372	36404	22484	178214	25418	522957	20867	902463	18208	2265818	11243
48	45372	36711	22484	182705	24787	529707	20668	906155	18208	2336487	11031
50	45372	36845	28908	188763	25512	526756	20018	908002	17585	2374489	10700
77	45372	37018	20678	194036	25558	541162	20079	909884	17685	2386860	10185
100	45372	37248	23237	198555	25297	554174	20038	941881	17633	2423700	10398
114	45372	37747	22484	203111	24791	559605	19255	941881	17633	2482988	10225
140	45372	37881	45772	207707	24211	576090	19036	949723	17613	2512801	11171
189	45372	38131	67453	212302	23612	593834	19047	950898	17251	2534432	10356
215	45372	38169	48181	216859	23566	599193	19047	961514	18351	2552550	10951
240	45372	38222	25550	221377	24015	599242	20112	964409	18349	2591588	11092
249	45372	39204	24662	231082	23889	563294	20112	973202	18437	2652177	13056
258	45372	41056	24662	234043	24020	599355	20112	987946	17780	2663924	11220
263	45372	42281	25041	241510	23642	599390	20112	999239	17928	2678190	11141
275	45372	43258	25003	247534	23613	599603	20112	1032702	17148	2708987	10705
308	45372	44784	24568	251300	23284	599678	20112	1041334	18626	2745427	10372
342	45372	46798	24624	256316	24182	599753	20112	1046099	16750	2818348	10662
381	45372	47801	23711	266113	23095	599644	20112	1053628	18487	2851334	10351
401	45372	49375	24596	270923	23302	600092	20112	1060216	19370	2875840	10450
481	45372	49973	24615	275519	23188	600307	21046	1064651	20588	2915573	10458
522	45372	52797	24503	280114	22993	603286	20391	1091562	17582	2985492	10218
562	45372	55319	27985	284709	22822	608692	20391	1128283	17610	3055404	10004
583	45372	57362	27759	289774	23237	608951	20297	1130718	18611	3084031	9936
671	45372	59916	27818	293825	22655	609158	20654	1138056	19508	3170509	9531
695	45372	62470	27845	298343	21487	610060	21934	1151984	16205	3197612	10677
770	45372	64684	27197	305748	24552	614391	20540	1158456	16119	3221783	10076
1575	45372	66545	27070	309451	24713	614391	18845	1167133	15905	3261793	9968
2117	45372	68731	27821	313895	23050	615454	19981	1225413	16438	3333409	9925
2247	45372	71561	27262	322041	23109	620209	20394	1233682	15720	3351444	8906
2515	45372	73511	26288	333835	23238	623983	18717	1245679	15929	3367715	9667
2600	45372	75617	28282	339805	22904	632032	19741	1257809	18131	3400884	9722
2651	45372	77107	27585	345480	22926	635880	18709	1270896	15830	3426623	9721
3238	45372	80098	27600	350211	23083	639185	18674	1328610	15994	3515196	10014
4647	45372	93087	28777	365401	22907	646916	18845	1332102	15994	3538404	9563
5405	45372	95744	27150	369995	23059	657895	18719	1333058	16310	3552172	9695
5920	44724	88250	27275	377139	22893	664707	18429	1361812	15369	3587282	9397
6438	44724	90753	26164	381458	22860	670258	18800	1409217	15033	3628968	9687
10205	44076	93676	26177	388953	23085	675629	18381	1420838	15083	3714488	9687
12099	43752	96731	25720	394927	20795	683778	17995	1439338	15280	3727124	10132
13539	43752	100644	29394	413913	20476	695462	18149	1450781	15190	3727124	9860
15131	44076	103873	26038	420040	20280	707382	17809	1475055	15086	3743601	9262
15131	44076	106945	26783	427699	19473	713511	19153	1486954	13775	3812368	9051
16443	44076	110031	26484	433777	20014	717317	19538	1493141	16179	3837473	8983
17859	44076	112138	26137	441315	19422	721801	19698	1704517	15489	3853307	8997
19451	42780	117224	27379	453021	19701	726027	18547	1717856	16218	3873901	8814
21041	42780	119749	23982	453062	19983	732073	19572	1733185	16162	3939991	8690
22457	42780	122781	27568	453302	21767	739410	19163	1756923	15981	4013708	8520
23973	42780	127078	27789	453573	22855	758976	19166	1805016	15484	4034185	8690
25615	42780	129734	27295	453718	21437	771293	19730	1825863	16702	4048577	8920
27005	41483	133387	26781	453750	21040	784510	19847	1870585	16452	4083847	8459
28420	42780	136228	26382	453978	21955	790678	18485	1987717	15581	4140381	8457
30112	41483	138401	26774	454332	21488	794757	19414	1995934	15498	4208380	8442
31476	41483	141599	25770	456346	20808	799482	18627	19942733	15064	4232232	8315
32815	41483	146333	25656	461741	21736	806691	18765	1987549	14317	4259848	8216
35771	41483	151040	25251	466294	21193	813453	19145	2014372	15159	4272310	8233
36648	8424	154423	25093	475708	21275	820790	18532	2046530	15053	4318004	8204
36667	16060	157487	25012	481972	21149	840301	18922	2135047	16889	4407062	9509
36686	17666	160514	25629	486804	20973	872095	18547	2138193	14834	4423059	8449

TABLE C-2. SUMMARY OF THA RESULTS  
(CONCLUDED)

CUMUL. CU FT	THA PPM	CUMUL. CU FT	THA PPM	CUMUL. CU FT	THA PPM	CUMUL. CU FT	THA PPM	CUMUL. CU FT	THA PPM
4473271	7886	7406155	19728	10446548	9721	27476554	2587	126772872	710
4515332	8010	7434121	17908	10505583	7197	27589207	3103	129726636	715
4613898	7995	7442079	8735	10612822	9482	29310684	3149	130587185	713
4644349	8296	7448003	11806	10660366	9318	31091820	3330	131438543	700
4675860	8603	7448603	16783	10886828	9858	34502784	3199	133319229	870
4737002	8418	7499541	17403	10903808	8630	35838121	3188	135078133	840
4846249	8373	7532379	10399	10903808	8630	37108593	3110	136980705	809
4867823	8312	7596556	12802	10903808	8630	39639889	3099	140740373	555
4884160	8292	7622875	15709	10913737	8830	39639889	1785	142650841	527
4935646	8159	7885060	16247	10938090	9130	39787697	2106	147245954	472
4968487	8063	7773839	16352	11297854	8349	39230228	2106	149999182	411
5082763	7937	7871140	15954	11293892	12275	39830228	2847	153741556	300
5187501	7767	7935301	15866	11371628	11332	39881741	2847	156531685	389
5304061	8350	7966231	14992	11392017	6478	40743381	1413	150527326	377
5334028	7970	8040535	13307	11472787	8823	41068297	3758	162444987	407
5416538	8362	8072302	17312	11496595	7392	41316283	4806	167373028	360
5425267	7404	8072302	17856	11539077	7290	41405668	5156		
5462853	7743	8138432	17870	11558387	8114	41405668	2778		
5532848	8044	8138432	17903	11981827	8797	41620757	2778		
5568770	7039	8228285	17024	12011457	2574	41620757	2981		
5588840	8924	8284299	12281	12110050	2967	42109406	3028		
5649050	8998	8315951	12272	12128130	3468	42826581	3017		
5764720	7078	8072302	9799	12415258	9748	44351258	2893		
5899879	8741	8103587	9247	12445838	2473	48198455	2714		
5899531	8768	8211334	14329	12550069	3845	48954520	2496		
6034491	6583	8297700	14361	12582284	4328	49088185	2931		
6059405	6469	8297700	12781	12703670	4255	50841125	2708		
6109115	7595	8391780	12642	12719899	2428	52274818	2740		
6241155	7309	8463196	14055	12739749	2428	53481860	2505		
6253640	7223	8562609	11002	12739749	2428	54971898	2403		
6320234	6812	8535732	12337	12807701	6235	55016965	3022		
6333130	6841	8617633	12322	12905542	8042	57915754	2704		
6462378	6456	8617633	13100	13195942	6754	58497118	2464		
6477359	6442	8731660	12184	13227448	2886	60637026	2379		
6477359	21487	8753386	13538	13339003	3089	60726798	2918		
6497230	21253	8857013	13984	13556932	2568	62348490	2618		
6528054	21867	8894968	13330	13593537	7320	63478105	2500		
6566691	21702	8927868	13439	13875865	7330	64739997	2344		
6621788	20958	9021615	13022	14062913	10271	69266314	1972		
6651857	21408	9028782	13022	14377852	9779	69266314	1768		
6656903	20561	9028782	11291	14455892	9208	73098814	1760		
6674813	21859	9124409	11121	14738205	8431	77272639	1950		
6718104	21725	9131225	891	14988788	8364	78538260	1725		
6740000	20184	9142477	894	15287843	7544	80038109	1425		
6748117	24473	9149294	11795	15312462	7727	81214498	1350		
6802483	24074	9158746	11709	15319329	7876	86640075	1200		
6836498	23386	9182019	11606	15852028	6372	90954599	1013		
6880943	22958	9306315	12120	15941484	5822	97982787	788		
6890680	23501	9322870	12168	17815174	5834	98245547	1044		
6912497	21956	9370871	11955	17815174	5893	99271148	972		
6985507	25805	9420932	12042	19691274	5622	102281581	896		
6993833	24992	9518805	12042	22242573	4984	106382334	888		
7052073	23846	9805834	10523	22250493	4672	107818330	892		
7081021	22153	9797587	10627	22299940	5374	112311723	808		
7134222	21509	9831172	10865	22943774	4884	116320948	792		
7139180	21729	9900964	10158	23448638	4745	120731484	708		
7235834	19306	10111861	10119	24268867	4794	122468475	728		
7248578	21001	10143243	4780	24998460	7805	123434789	535		
7248578	20870	10214785	4457	25008198	4932	125648770	315		
7310793	21571	10225667	12359	25679708	4615	126475783	365		
7349128	20277	10236685	11454	26733313	2581	128254863	665		

1

APPENDIX D  
ORNL CALCULATIONS OF BIODEGRADATION

TABLE D-1. ORNL CALCULATIONS OF BIODEGRADATION

CALCULATION OF BIODEGRADATION BASED ON CARBON DIOXIDE  
AND OXYGEN MEASUREMENTS IN EXTRACTED GAS

DATE	TIME	CUMULATIVE STD. FT3 EXTRACTED	PERCENT CO2 IN OFF-GAS	PERCENT O2 IN OFF-GAS	LBS HC <sub>4</sub> IN INTERVAL CO2 BASIS	LBS HC <sub>4</sub> IN INTERVAL O2 BASIS	CUMULATIVE LBS HC <sub>4</sub> CO2 BASIS	CUMULATIVE LBS HC <sub>4</sub> O2 BASIS
18-Dec-88	1418	3800	11	1	17.0	19.3	17	19
18-Dec-88	1940	12000	9	1.8	33.4	40.9	50	60
19-Dec-88	1000	31700	7.5	3.8	66.1	91.3	116	152
06-Jan-89	2245	46900	5.15	11.7	39.0	51.3	156	203
07-Jan-89	900	57600	4.25	12.4	39.4	47.2	195	250
07-Jan-89	1552	81400	4.1	13.5	23.3	28.3	218	278
08-Jan-89	215	102000	1.8	13.9	24.5	38.3	243	317
08-Jan-89	1015	119000	4.2	13.7	20.6	31.2	263	348
08-Jan-89	1715	133000	3.85	13.7	22.8	26.0	286	374
08-Jan-89	1840	136000	3.35	15.9	4.4	4.7	291	378
08-Jan-89	2200	142000	3.45	14.5	8.2	8.9	299	387
09-Jan-89	250	166000	2.55	16.1	29.1	34.3	328	422
09-Jan-89	1810	184000	2.5	16.5	18.3	21.5	346	444
10-Jan-89	1300	241000	2.4	17.1	56.2	81.0	402	505
10-Jan-89	1600	251000	2.3	17.1	9.5	9.6	412	515
11-Jan-89	830	296000	2.3	19.1	41.6	33.2	453	548
13-Jan-89	915	445000	5.2	1.7	230.6	410.2	684	958
18-Jan-89	1615	457000	3.45	13.9	15.6	30.2	700	988
18-Jan-89	2100	473000	3.2	15.6	21.5	25.5	721	1014
18-Jan-89	245	516000	1.4	16.2	39.8	55.8	761	1070
19-Jan-89	1509	533000	2.7	16.4	14.0	20.3	775	1090
19-Jan-89	2135	556000	2.5	16.8	24.1	25.8	799	1116
20-Jan-89	935	549000	2.5	17.2	43.3	43.8	843	1159
21-Jan-89	1540	605000	2.9	15.9	6.5	6.8	849	1166
22-Jan-89	1100	648000	2.8	16.1	48.4	54.7	898	1221
23-Jan-89	1500	728000	2.5	17.1	25.4	39.6	924	1311
24-Jan-89	1300	800000	1.1	17.4	51.9	68.7	1026	1379
25-Jan-89	1415	895000	1.7	17.6	43.0	82.2	1089	1462
26-Jan-89	1430	965000	1.8	17.9	50.5	56.1	1139	1518
27-Jan-89	1415	1055000	1.6	19.1	63.0	98.7	1202	1586
28-Jan-89	1715	1156000	1.7	16.4	66.8	70.7	1269	1657
29-Jan-89	1315	1233000	1.6	18.4	50.8	51.0	1320	1708
31-Jan-89	1530	1438000	1.4	15.5	122.6	133.1	1442	1841
01-Feb-89	1715	1501000	1.3	18.3	66.1	73.8	1508	1915
07-Feb-89	1530	2207000	1	19.3	294.2	320.7	1803	2236
09-Feb-89	950	2487000	0.70	19.7	28.3	106.9	1901	2343
14-Feb-89	1400	3184000	0.22	20.4	131.8	168.6	2035	2511
21-Feb-89	1300	4484000	1.7	15.3	491.1	546.1	2526	3057
23-Feb-89	1330	4944000	0.2	20.8	171.9	169.8	2698	3227
11-Mar-89	2040	6326000	5	7	93.1	70.4	2791	3297
12-Mar-89	754	6357000	4.2	10	64.1	98.7	2855	3396
12-Mar-89	1535	6396000	3.5	12.3	60.8	97.3	2916	3494
13-Mar-89	900	6450000	3.5	13.9	76.4	108.6	2992	3602
13-Mar-89	1700	6460000	3.5	14.6	42.5	50.4	3035	3653
14-Mar-89	915	6547000	3.1	15.5	88.2	90.9	3124	3752
15-Mar-89	1300	6647000	2.8	15.9	119.0	134.9	3243	3887
15-Mar-89	1015	6581000	2.3	16.2	240.3	294.9	3483	4162
20-Mar-89	1000	7070000	2.8	16.4	196.4	225.2	3679	4408
22-Mar-89	1120	7247000	0.6	20	113.1	126.2	3793	4534
01-Apr-89	1000	8178000	2.1	16.8	500.0	624.4	4283	5138
15-Apr-89	1430	11440000	1.34	19	2244.7	2533.0	6527	7671

APPENDIX E  
*IN SITU* MOISTURE CONTENT MEASUREMENTS

TABLE E-1. WATER CONTENT IN SOIL: NEUTRON ACCESS TUBE 1

Depth (ft)	9/16/88	11/10/88	1/12/89	6/8/89	8/10/89	10/12/89
1	15.6	5.9	7.2	5.8	0.2	0.8
2	13.2	13.3	14.0	11.9	1.7	1.7
3	9.2	10.2	12.4	10.4	2.5	1.6
4	7.5	8.3	11.5	10.1	6.1	4.1
5	7.9	8.0	11.2	10.2	6.8	6.2
6	8.9	8.2	11.2	10.3	8.2	7.0
7	9.1	9.6	11.3	10.5	9.5	3.8
8	8.5	8.9	10.5	9.9	9.6	8.4
9	9.9	9.9	12.4	10.9	11.8	10.3
10	10.2	10.4	12.5	11.5	11.1	10.9
11	15.9	12.9	18.8	15.6	14.5	13.3
12	18.8	20.7	25.3	23.6	23.9	20.5
13	10.6	10.9	13.2	13.5	11.5	11.2
14	8.5	8.0	8.6	9.6	9.3	8.5
15	9.9	9.8	9.2	11.2	10.4	8.6
16	9.8	9.3	8.8	11.1	10.1	8.8
17	8.7	8.2	7.6	10.3	9.2	8.5
18	8.5	8.0	7.9	10.2	9.5	8.4
19	9.8	8.9	8.6	11.2	10.1	9.4
20	10.0	9.3	9.3	11.9	10.5	9.4
21	9.6	8.6	8.5	11.1	10.5	9.3
22	10.7	10.7	10.4	12.2	10.5	9.9
23	8.6	8.2	8.2	9.6	9.2	8.3
24	8.9	8.2	8.5	10.4	10.0	9.1
25	16.2	14.5	13.6	17.9	17.9	17.1
26	11.5	11.5	12.2	14.2	12.5	12.7
27	9.0	8.2	7.9	10.3	11.6	9.9
28	9.8	11.9	12.2	12.3	11.6	11.3
29	5.4	5.2	5.2	5.4	5.9	5.6
30	6.5	5.7	5.9	6.1	6.2	6.2
31	25.8	22.7	24.0	26.1	21.3	24.7
32	12.2	10.9	11.5	10.7	14.6	10.5
33	7.6	10.9	11.1	9.0	7.7	7.7
34	8.0	10.1	9.9	9.4	9.3	9.0
35	7.2	9.2	9.3	8.1	7.9	7.4
36	6.8	6.4	8.2	6.9	6.4	6.5
37	6.7	6.5	7.9	7.0	6.9	6.5
38	7.5	7.1	7.9	8.2	7.7	7.6
39	6.7	6.7	6.9	6.3	4.8	4.8
40	7.5	7.6	7.5	6.9	6.9	6.4
41	9.6	10.9	11.1	10.2	10.6	9.6
42	7.6	9.0	8.8	8.4	8.5	8.0
43	8.5	9.5	9.2	9.0	8.4	8.2
44	9.8	10.5	11.3	10.6	10.1	10.5
45	7.2	6.7	7.1	7.3	7.5	7.5



TABLE E-2. WATER CONTENT IN SOIL: NEUTRON ACCESS TUBE 2

Depth (ft)	9/15/88	11/10/89	1/12/89	6/8/89	8/10/89	10/12/89
1	6.0	5.5	60.4	4.9	0.8	1.2
2	11.8	16.4	27.3	14.5	2.5	2.1
3	10.2	12.9	20.3	12.4	4.2	3.2
4	10.6	10.2	13.9	12.7	7.8	6.5
5	9.6	9.5	17.3	10.0	8.5	7.0
6	10.7	9.5	18.0	12.3	9.5	9.0
7	11.5	11.2	17.4	12.7	11.4	10.1
8	9.9	10.5	15.8	12.2	11.0	8.7
9	9.5	9.3	14.0	11.2	10.1	7.3
10	25.3	24.9	27.9	27.1	26.2	25.1
11	8.5	7.8	10.2	8.9	8.7	7.8
12	8.5	7.1	8.8	8.0	8.9	6.5
13	15.1	13.2	12.7	14.1	13.2	11.8
14	8.4	8.2	7.6	8.7	8.7	7.1
15	6.9	7.2	7.2	7.5	10.5	7.6
16	7.5	7.5	6.7	8.1	10.5	8.9
17	5.3	6.0	6.0	6.1	8.9	7.5
18	6.2	6.1	6.0	5.8	8.9	7.3
19	6.8	6.7	6.9	7.0	8.8	7.1
20	6.9	7.3	7.0	7.2	8.2	7.2
21	9.8	10.4	9.9	10.6	10.8	10.2
22	12.5	10.8	12.4	12.3	14.4	12.7
23	15.6	16.2	15.8	15.3	16.2	15.2
24	12.1	14.3	12.3	12.5	11.9	12.1
25	8.1	8.0	7.6	7.2	8.2	8.3
26	7.2	7.3	7.5	7.7	9.0	9.2
27	9.6	9.9	9.2	10.3	11.2	12.4
28	10.8	10.7	10.5	10.7	10.4	11.5
29	9.2	9.9	9.2	8.3	8.2	8.3
30	5.6	5.9	6.1	5.2	5.9	5.1
31	6.5	6.2	6.5	6.4	6.5	6.9
32	11.0	10.3	10.1	9.8	9.9	12.0
33	8.7	8.5	3.3	7.9	8.5	11.9
34	8.7	9.1	3.4	8.1	8.2	10.8
35	9.2	9.2	9.2	9.0	8.5	10.4
36	8.0	7.7	8.1	7.8	7.9	7.9
37	10.5	10.0	9.4	10.8	12.7	11.0
38	24.9	20.2	17.6	21.2	29.6	22.6
39	40.3	37.5	39.2	37.2	34.2	34.1
40	39.9	38.9	38.3	38.1	39.0	37.1
41	38.3	39.0	39.2	37.8	37.5	37.2
42	38.0	36.4	37.2	37.7	37.5	37.4
43	34.3	33.3	32.5	33.7	34.0	33.2
44	35.8	33.7	35.2	35.8	35.0	35.0
45	35.0	33.8	33.6	34.5	34.7	35.1

TABLE E-3. WATER CONTENT IN SOIL: NEUTRON ACCESS TUBE 3

Depth (ft)	9/16/88	11/10/88	1/12/89	6/8/89	8/10/89	10/12/89
1	7.9	3.8	6.2	5.0	1.2	1.9
2	9.9	8.3	12.9	12.3	4.8	5.2
3	8.1	7.5	10.9	10.2	7.5	6.4
4	7.5	7.2	10.9	10.2	8.4	7.1
5	8.3	8.1	11.0	10.5	9.9	8.6
6	8.1	8.2	11.0	10.6	10.2	8.9
7	8.2	8.4	11.0	10.3	10.2	8.8
8	8.2	8.5	11.2	10.8	9.9	9.5
9	7.9	8.0	11.2	9.5	9.5	8.2
10	7.6	7.3	10.7	9.0	9.2	8.3
11	8.6	8.5	8.8	10.3	9.9	9.4
12	8.9	8.6	8.9	10.6	10.6	8.9
13	9.3	8.5	8.9	10.5	9.5	9.2
14	9.4	8.5	8.3	10.7	9.6	9.6
15	10.7	9.4	8.8	11.5	10.3	9.6
16	8.8	7.5	6.9	9.2	8.2	7.7
17	9.2	8.6	7.7	10.5	8.8	8.3
18	10.2	9.8	9.1	11.2	10.7	9.4
19	9.7	9.0	8.5	10.9	9.2	8.6
20	12.3	10.9	10.6	12.9	11.5	10.8
21	8.9	8.9	8.5	9.8	9.1	8.8
22	9.9	9.8	9.5	11.2	11.2	9.3
23	12.5	11.6	11.4	14.0	13.0	11.9
24	21.1	19.6	17.1	23.3	21.9	17.6
25	12.9	12.5	11.8	13.9	13.5	13.1
26	9.2	9.1	9.4	11.6	10.8	10.2
27	8.1	7.8	8.0	9.5	9.5	8.8
28	9.1	8.5	8.2	9.5	11.1	10.0
29	9.2	8.5	8.7	10.5	10.4	9.8
30	8.3	8.2	7.8	9.3	10.6	8.6
31	11.5	12.2	10.9	13.7	19.7	12.7
32	15.0	14.7	14.7	17.6	18.9	16.6
33	7.0	6.8	7.0	8.4	9.0	8.2
34	7.0	6.7	7.3	7.7	9.3	9.2
35	8.1	6.2	5.8	6.9	7.5	7.9
36	7.0	6.9	6.4	6.1	7.1	7.8
37	7.3	6.5	6.4	5.8	5.5	6.1
38	22.0	6.6	6.7	6.6	6.4	6.7
39	22.5	19.6	23.3	21.9	21.8	20.9
40	28.6	24.6	24.9	26.6	26.0	25.9
41	5.5	5.7	5.9	5.9	5.5	6.0
42	4.2	4.3	4.4	4.3	4.3	4.0
43	4.4	4.2	4.5	4.4	4.6	4.5
44	5.1	5.0	4.8	4.9	4.9	5.2
45	N/D	5.8	5.2	5.3	5.1	5.0

APPENDIX F  
SUMMARY OF FLOW TESTS

TABLE F-1. EXTRACTION RATES FROM EACH VENT\*

EXTRACTION RATES FROM EACH VENT - HILL AFB SOIL VENTING FLOW TESTS  
FLOW RATES IN STANDARD CUBIC FEET PER MINUTE (INLET FLOWS NEGATIVE)

TEST	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
V1																	173			
V2																				193
V3																?				
V4											?									
V5																		103	104	
V6																				
V7	33	50	110						214						?		250	96	177	278
V8																				
V9					-15		194	214			?	?	?	?	?	?		93		
V10				62	68					178										
V11					-15									?				74		
V12																				
V13																				
V14														?						
V15												?								
V16																				
V17																				
V18																				
V19						206														
V20																				
TOTAL	33	50	110	62	38	206	194	214	214	178	311	315	252	433	345	420	423	371	281	471

TEST	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
V1							211										?	?	?	
V2							244										?	?	?	
V3						264				231	280	211						?		
V4						77				52	67	73						?		
V5	57			128			211										?	?	?	
V6	78	152																?		
V7	25		292	111			276										?	?	?	
V8	76	108																?	?	
V9	40				127	202				151	187	190						?		244
V10	45	103								121		147						?		115
V11	46				75	140				78	116	138						?	?	422
V12			243	96													?	?	?	
V13				108														?	?	
V14					114					131	181	140						?		
V15					83					198	231	217						?		
V16																?	30			
V17													33	140	154	53				
V18									29						?	71				
V19								332	332				362	100	128	62				
V20									29											
TOTAL	167	370	535	439	1094	683	942	332	274	1062	1051	620	303	440	444	445	1021	1133	?	541

\* ? = undetermined; only the total flowrate was measured.

TABLE F-2. FLOW TEST RESULTS

Hole	X (ft)	Y (ft)	Z at top depth (ft)	TEST	VACUUM AT PT. INCHES OF WATER																									
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20						
V1	14.56	109.4	4155.4		0.66	0.26	0.17					1.66	0.55	1.34	1.14	1.03	1.8	2.51	2.32	2.52	2.92	4.75	4.75							
V2	54.8	109.4	4155.1		0.92	0.50	0.33					2.25	1.1	2.5	2.04	1.84	3.1	3.8	5.05	3.41	4.7	2.92								
V3	89.41	108.1	4156.2		0.74	0.82	0.64					1.44	1.85	1.95	3.9	3.15	2.9	4.4	4.1	25.2	3.38	3.62	3.45	5.5						
V4	129.1	106.4	4156.2		0.44	0.86	0.73					1.63	2.15	2.05	3.02	2.87	3	3.53	2.77	5.8	2	2.97	2.06	2.95						
V5	132.2	71.9	4154.9		0.97	0.28	0.25					0.85	1.3	2.35	0.72	1.68	1.55	1.21	2.5	3.57	2.48	5.7	1.32	2.69	5.2					
V6	32.94	71.12	4155.1		0.361	0.88						1.5	2	4.3	1.15	2.53	2.34	1.92	3.66	6.2	3.8	7.95	6.35	10.2	8.5					
V7	52.97	70.08	4156.6		2.426	3.6						2.1	2.69	1.91	1.5	3.55	3.2	2.74	5.35	2.5	13.4	27.4	28.7							
V8	70.46	68.07	4155.5									0.49	0.77	2.0	2.43	4.4	2.05	5.55	4.95	4.15	7.8	8.3	7.3	6.9	6.45	7.0	8.8			
V9	84.23	68.08	4155.9									0.49	0.77	2.0	2.43	4.4	2.05	5.55	4.95	4.15	7.8	8.3	7.3	6.9	6.45	7.0	8.8			
V10	107.6	67.51	4155.5									0.49	0.77	2.0	2.43	4.4	2.05	5.55	4.95	4.15	7.8	8.3	7.3	6.9	6.45	7.0	8.8			
V11	127.7	66.72	4155.7									0.49	0.77	2.0	2.43	4.4	2.05	5.55	4.95	4.15	7.8	8.3	7.3	6.9	6.45	7.0	8.8			
V12	11.53	32.02	4154.9									0.46	1.51	0.67																
V13	51.57	30.21	4155.3									0.46	1.51	0.67																
V14	86.77	27.72	4156.2									0.46	1.51	0.67																
V15	127.1	30.41	4156.8									0.46	1.51	0.67																
V16	127.1	30.41	4156.8									0.46	1.51	0.67																
V17	127.1	30.41	4156.8									0.46	1.51	0.67																
V18	127.1	30.41	4156.8									0.46	1.51	0.67																
V19	127.1	30.41	4156.8									0.46	1.51	0.67																
V20	127.1	30.41	4156.8									0.46	1.51	0.67																
V21	127.1	30.41	4156.8									0.46	1.51	0.67																
V22	127.1	30.41	4156.8									0.46	1.51	0.67																
V23	127.1	30.41	4156.8									0.46	1.51	0.67																
V24	127.1	30.41	4156.8									0.46	1.51	0.67																
V25	127.1	30.41	4156.8									0.46	1.51	0.67																
V26	127.1	30.41	4156.8									0.46	1.51	0.67																
V27	127.1	30.41	4156.8									0.46	1.51	0.67																
V28	127.1	30.41	4156.8									0.46	1.51	0.67																
V29	127.1	30.41	4156.8									0.46	1.51	0.67																
V30	127.1	30.41	4156.8									0.46	1.51	0.67																
V31	127.1	30.41	4156.8									0.46	1.51	0.67																
V32	127.1	30.41	4156.8									0.46	1.51	0.67																
V33	127.1	30.41	4156.8									0.46	1.51	0.67																
V34	127.1	30.41	4156.8									0.46	1.51	0.67																
V35	127.1	30.41	4156.8									0.46	1.51	0.67																
V36	127.1	30.41	4156.8									0.46	1.51	0.67																
V37	127.1	30.41	4156.8									0.46	1.51	0.67																
V38	127.1	30.41	4156.8									0.46	1.51	0.67																
V39	127.1	30.41	4156.8									0.46	1.51	0.67																
V40	127.1	30.41	4156.8									0.46	1.51	0.67																
V41	127.1	30.41	4156.8									0.46	1.51	0.67																
V42	127.1	30.41	4156.8									0.46	1.51	0.67																
V43	127.1	30.41	4156.8									0.46	1.51	0.67																
V44	127.1	30.41	4156.8									0.46	1.51	0.67																
V45	127.1	30.41	4156.8									0.46	1.51	0.67																
V46	127.1	30.41	4156.8									0.46	1.51	0.67																
V47	127.1	30.41	4156.8									0.46	1.51	0.67																
V48	127.1	30.41	4156.8									0.46	1.51	0.67																
V49	127.1	30.41	4156.8									0.46	1.51	0.67																
V50	127.1	30.41	4156.8									0.46	1.51	0.67																
V51	127.1	30.41	4156.8									0.46	1.51	0.67																
V52	127.1	30.41	4156.8									0.46	1.51	0.67																
V53	127.1	30.41	4156.8									0.46	1.51	0.67																
V54	127.1	30.41	4156.8									0.46	1.51	0.67																
V55	127.1	30.41	4156.8									0.46	1.51	0.67																
V56	127.1	30.41	4156.8									0.46	1.51	0.67																
V57	127.1	30.41	4156.8									0.46	1.51	0.67																
V58	127.1	30.41	4156.8									0.46	1.51	0.67																
V59	127.1	30.41	4156.8									0.46	1.51	0.67																
V60	127.1	30.41	4156.8									0.46	1.51	0.67																
V61	127.1	30.41	4156.8									0.46	1.51	0.67																
V62	127.1	30.41	4156.8									0.46	1.51	0.67																
V63	127.1	30.41	4156.8									0.46	1.51	0.67																
V64	127.1	30.41	4156.8									0.46	1.51	0.67																
V65	127.1	30.41	4156.8									0.46	1.51	0.67																
V66	127.1	30.41	4156.8									0.46	1.51	0.67																
V67	127.1	30.41	4156.8									0.46	1.51	0.67																
V68	127.1	30.41	4156.8									0.46	1.51	0.67																
V69	127.1	30.41	4156.8									0.46	1.51	0.67																
V70	127.1	30.41	4156.8									0.46	1.51	0.67																

TABLE F-2. FLOW TEST RESULTS  
(CONTINUED)

VACUUM AT PT. INCHES OF WATER																									
TEST																									
Z at top depth																									
1																									
2																									
3																									
4																									
5																									
6																									
7																									
8																									
9																									
10																									
11																									
12																									
13																									
14																									
15																									
16																									
17																									
18																									
19																									
20																									

TABLE F-2. FLOW TEST RESULTS  
(CONTINUED)

VACUUM AT PT. - INCHES OF WATER

Node	X (ft)	Y (ft)	Z (ft)	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
V1	14.56	103.9	4755.4	2.74	2.84	3.9	6.3	1.38	3.17	3.7	0.21	0.08	3.07	3.1	2.75					27.6	17	
V2	54.8	103.4	4755.1	3.4	3.7	4.35	6.2	2.17	6.9	4.3	0.43	0.31	5.8	5.7	5.2					29	17.4	
V3	89.41	103.1	4756.2	3.8	3.93	3.68	4.6	3.64	3.68	8.3	1.1	0.51	3.2	3.2	30.5					55	17.5	
V4	129.1	106.4	4756.2	2.87	2.95	2.25	2.94	3.7	34.8	4.6	2	1	54.2	34.5	32.7					2.8	18	5.9
V5	13.22	71.9	4754.9	9.2	4.7	6.7	28.2	1.88	3.25	39.2	0.33	0.12	3.6	3.5	3.05					27.6	16.2	34.5
V6	32.94	71.12	4755.1	9.4	15.7	9.7	11.2	2.8	5.4	17.2	0.47	0.2	3.6	3.5	3.05					15.4	16.5	
V7	52.97	70.08	4756.6	9.4	7.2	35.3	28.8	3.72	7.05	41.3	0.63	0.34	7.45	7.4	6.2					27.8	16.5	
V8	70.48	68.87	4755.8	9.5	10	8.8	10.6	5.45	10.5	13	0.8	0.26	11.1	10.6	9.4					10.2	16.7	
V9	88.23	68.08	4755.9	9.65	9.95	5.7	7.4	17.5	31.7	9.3	1.29	0.64	32.8	32.9	31					0.6	0.7	17
V10	107.6	67.51	4755.5	9.8	16.5	39.2	53.2	7.8	11.1	8.65	2	1.18	32.9	32.9	31					0.72	0.33	0.6
V11	127.7	66.72	4757	9.5	4.4	2.62	3.6	17.8	34	4.5	3.35	1.91	33	33.2	31.5					2.68	17	3.85
V12	11.53	32.02	4754.9	2.63	2.78	35.3	29.4	1.72	2.37	7.3	0.31	0.1	3	2.9	2.58					28.2	16.6	
V13	51.57	30.21	4755.3	3.55	3.86	6.45	2.9	3.55	4.5	7.0	0.57	0.21	6.4	6.3	5.7					28	16.8	
V14	86.77	27.72	4756.2	3.4	3.74	4.1	6.9	17.4	6.5	3.95	1.15	0.55	32.5	32.6	31					0.68	0.38	0.6
V15	127.1	28.43	4756.8	3.32	3.37	2.46	3.65	17.7	8	3.62	2.85	1.62	31	31.5	29.5					2	2.75	16.5
RST-1	30.26	95.46	4757.4																			
A	90.02	128.4	4756.2	2.95	3.2	3.2	3.3	2.33	11.7	8.7			12	11.7	9.4					0.44	0.59	0.78
B	88.62	88.29	4756.2	5.65	6.3	5.55	7	5.95	14.1	10.6			17	16	14					0.71	0.36	0.71
C	107.2	86.9	4756.7	3.7	3.9	2.88	3.8	4.8	11.8	5.45			1.4	13.1	10.4					0.65	1.19	0.65
E	107	96.08	4756.6	0	0	0	0	0	0	0										0	0	0
F	110.9	85.74	4756.8	4.9	5.5	3.52	4.75	6.05	13.8	6.8			17.1	15	12.1					0.69	1.32	4.25
H	95.69	81.75	4756.3	5.9	6.55	4.9	6.3	6.9	14.6	8.9			18.6							0.42	0.85	6.15
J	90.61	76.21	4756.4	0	0	0	0	0	0	0			10.6	10.2	9.1					0.49	0.13	0.55
K	50.37	76.23	4755.3	7.1	8.1	11	12.9	4.55	9.9	17.5			20.2	18.1	15.1					0.45	0.2	1.2
M	90.41	74.56	4756.2	6.8	7.2	5.3	6.9	6.6	16	9.1			10.6	10.2	9.1					0.62	0.81	0.37
N	94.59	72.57	4756.2	4.05	3.62	3.63	3.55	3.55	3.55	3.2			6	4.8	5.5					0.37	0.75	6.6
P	0	77.75	4755.3	3.82	3.11	0	11.4	1.94	2.5	14.1			2.7	2.6	2.3					0.15	0.01	3
Q	94.76	68.2	4756	7.1	7.65	5.23	6.9	9.5	17.2	8.7			22.2	19.2	15.2					0.63	0.82	0.41
R	84.21	60.28	4755.7	7	7.6	6.55	8.7	6.1	14.1	10.4			19.4	17.8	15.5					0.67	0.8	12
S	45.73	63.93	4755.4	3.1	3.1	6.1	7.3	2	29.2	7			2.43	2.4	2.16					0.14	0.14	4.8
T	44.43	65.71	4755.2	7.55	8.7	12.7	11.3	3.88	6.7	19.4			6	6.2	4.7						17	15.1
U	31.39	69.73	4755.2	2.35	2.38	4.4	5.65	1.5	2.1	5.2			1.75	1.7	1.62						3.75	3
W	40.18	55.38	4755.2	4.3	4.8	7.9	11.2	2.4	3.76	10			4	3.95	3.55					10.4	8.2	
X	30.41	50.95	4755.1	1.74	1.8	3.33	4.83	1.06	1.67	3.9			1.5	1.25	1.13					4.5	2.5	
Y	35.06	51.27	4755.2	6.5	7.15	11.4	17.2	3.5	5.0	16.5			7.1	6.95	6.15					17.2	14.2	
Z	29.88	46.1	4755	3.16	3.4	7.7	10.8	1.9	2.67	8			2.98	2.87	2.62					10.4	7.3	
AA	51.8	8.525	4755.4	2.5	2.77	5.15	9.7	3.2	3.23	5.3			5.5	5.15	4.9					0.64	0.31	0.56
BB	84.35	7.086	4756	2.24	2.46	3.25	5.95	4.8	5.55	4.95			8.5	8.3	7.7						4.9	6.1
NA1	50.44	51.1	4755.5																			
NA2	34.79	95.53	4755.6																			
NA3	30.88	0	4755																			
32	47.63	62.41	4756.8	4.4	4.5	8.9	10.3	2.58	4.3	10.5			4.1	4	3.58					8.8	6.7	
33	35.12	45.95	4755.4	1.56	1.58	3.1	4.63	1.08	1.5	3.2			1.18	1.19	1.08					2.6	2.15	
34	44.34	72.8	4756.6	6.4	7	11.2	13.8	3	5.75	17			6	5.95	5.2					14.5	12	
35	24.68	79.47	4755.7	3.27	3.3	4.3	7.6	1.98	2.5	10			2.37	2.35	2.08					8.4	5.4	
36	34.07	63.97	4755.7	5.6	6.7	8.4	12.3	2.28	4	13.1			4.15	4.05	3.66					12.8	10.6	
37	54.63	80.4	4757	0	0	0	0	0	0	0										0	0	
38	54.72	96.85	4757.2	4.85	5.35	6.6	8.6	3.15	8.9	21			8.9	8.5	7.55					15.6	13.5	
39	42.52	86.51	4756.7	6.8	7.5	10.4	13.6	3.28	7.2	20			7.65	7.6	6.7					16.3	14.3	
40	59.52	68.23	4757.1	3.83	4.1	5.85	6.7	2.83	6.55	9.2			5.6	5.5	4.85					6.9	7	
U&W	38.77	57.55	4755.2	2.31	2.35			6.75	1.48	2.08			1.72	1.7	1.58					3.6	2.8	

TABLE F-2. FLOW TEST RESULTS  
(CONCLUDED)

VACUUM AT PT. BICHES OF WATER

Hole	X (FT)	Y (FT)	Z at top		21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
XY233	32.62	48.57	4755.2	173	175	33	485	113	168	36	128	127	118										
NA18V	61.01	40.65	4755.4	223	235	375	97	218	27	416													
SA12	46.68	63.17	4756.1	507	305	81	72	292	69														
Y13AA	61.69	19.37	4755.4	138	148	248	61	183	19	253													
MA8N	93.5	73.66	4755.2	43	455	362	46	64	103	67													
JA4	97.65	79	4756.3	335	355	267	316	435	87	41													
BA20	68.42	78.18	4756	445	49	426	54	526	133	7													
B	68.82	68.29	4756.2	395	43	38	40	446	117	695													
BAV3	69.01	66.19	4756.2	365	377	347	445	58	128	885													
CEP	104.9	84.32	4756.8	37	368	278	388	49	118	62													
V34A	69.71	118.3	4756.2	248	262	25	317	268	109	68													
A	90.02	126.4	4756.2	197	204	198	282	2	83	445													
24TV8	89.64	69.19	4755.8	515	63			68	142														
52FV3	91.29	71.14	4755.5	495	618			82	103														
72FV9	92.47	72.32	4757						111														
1FV7	51.67	68.78	4756.8	425	41	91	56																
2FV7	40.79	66.9	4756.6	378	37	775	86			95													
3FV7	48.85	65.96	4756.8	355	35	87	82			85													
4FV7	47.91	65.02	4756.8	34	335	645	78			8													
1	192	60.4	4744.5	975	972	954				15													
2	169.7	62	4744.2					185															
3	185.7	61.9	4744.1	083						084													
4	181.6	62	4743.9					089															
5	174.8	60.8	4744.2					097															
6	187.7	65.8	4744.4	084				098															
7	183.7	63.7	4744.3		083	081																	
8	178.8	61.3	4744.1		082	087		102															
9	169.3	61.4	4744.2		082	087																	
10	166	60.1	4744.1																				
11	181.4	69.3	4743.8	096	091			086															
12	194.4	78.4	4744.4		084																		
13	189.3	78.1	4743.8			059																	
14	185.1	78	4744.2	092				092															
15	191	77.4	4743.6					093															
16	171.7	71.8	4744.6					093															
17	185.8	80.3	4744.7	090	091			25															
18	182.7	80.4	4744.4	103																			
19	178.8	80.1	4744.7			082	096																
20	188.9	84.4	4744.1	102																			
21	184.8	84.2	4744.1					204															
22	180.6	84	4744.4																				
23	196.2	97	4744.5		101	079																	
24	159.4	94.3	4744.3		134	068	128	215	475	188													
25	195.4	112.8	4744.6					326															
26	181.7	113.1	4744.2	103		088		176	388	137													
27	169.1	112.7	4745.2					121															
28	181.1	132.8	4744.3		128																		
29	181	132.8	4744.3		084			079															
30	168.5	132	4744.6	094																			
35	171.7	77.8	4744.6	189	183	125	182	376	635	2													
36	193.7	132.2	4744.8																				



APPENDIX G  
POST-VENTING CHARACTERIZATION

TABLE G-1. POST-VENTING HYDROCARBON ANALYSES:  
BORINGS FROM VERTICAL VENT AREA

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type*	(mg/kg)	Samp No.	Date	No.
V2A	1.5	3.0		37	4680	891106	233
V2A	4.5	6.0		66	4681	891106	234
V2A	7.5	9.0		32	4682	891106	235
V2A	10.5	12.0		26	4683	891106	236
V2A	10.5	12.0	F	34	4684	891106	237
V2A	13.5	15.0		32	4685	891106	238
V2A	18.5	20.0		424	4686	891106	239
V2A	23.5	25.0		67	4687	891106	240
V3A	18.5	20.0		53	4662	891107	040
V3A	23.5	25.0		115	4663	891107	041
V3A	28.5	30.0		300	4664	891107	042
V3A	33.5	35.0		193	4665	891107	043
V3A	33.5	35.0	F	40	4666	891107	044
V3A	37.0	38.5		223	4667	891107	045
V3A	38.5	40.0		34	4668	891107	046
V4A	2.0	3.0	JMC	71	4609	891102	263
V4A	4.0	5.0	JMC	<20	4610	891102	264
V4A	7.5	9.0		31	4613	891102	267
V4A	10.5	12.0		26	4614	891102	268
V4A	10.5	12.0	F	23	4615	891102	269
V4A	13.5	15.0		23	4616	891102	270
V4A	18.5	20.0		35	4653	891107	031
V4B	1.5	3.0		26	4654	891107	032
V4B	4.5	6.0		31	4655	891107	033
V4B	7.5	9.0		33	4656	891107	034
V4B	10.5	12.0		34	4657	891107	035
V4B	13.5	15.0		28	4658	891107	036
V4B	13.5	15.0	F	37	4659	891107	037
V4B	17.0	18.5		26	4660	891107	038
V4B	18.5	20.0		40	4661	891107	039
V4c	1.5	3.0		23	4707	891107	304
V4c	4.5	6.0		36	4708	891107	305
V4c	7.5	9.0		28	4709	891107	306
V4c	10.5	12.0		35	4710	891107	307
V4c	13.5	15.0		30	4711	891107	308
V4c	16.5	18.0		220	4712	891107	309
V4c	18.5	20.0		35	4713	891107	310
V4c	28.5	30.0		70	4714	891107	311
V4c	33.5	35.0		82	4715	891107	312
V6A	38.5	40.0		33	4688	891106	241
V6A	43.5	45.0		37	4689	891106	242
V6A	48.5	50.0		80	4690	891106	243
V6A	53.5	55.0		42	4691	891106	244
V7A	1.5	3.0		31	4701	891106	254
V7A	4.5	6.0		34	4702	891106	255

TABLE G-1. POST-VENTING HYDROCARBON ANALYSES:  
BORINGS FROM VERTICAL VENT AREA  
(CONTINUED)

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type*	(mg/kg)	Samp No.	Date	No.
V7A	7.5	9.0		25	4703	891106	256
V7A	10.5	12.0		23	4704	891106	257
V7A	10.5	12.0	F	36	4705	891106	258
V7A	13.5	15.0		36	4706	891106	259
V8A	1.5	3.0		24	4692	891106	245
V8A	4.5	6.0		37	4693	891106	246
V8A	23.5	25.0		35	4694	891106	247
V8A	26.0	27.5		25	4695	891106	248
V8A	28.5	30.0		62	4696	891106	249
V8A	33.5	35.0		35	4697	891106	250
V8A	38.5	40.0		71	4698	891106	251
V8A	43.5	45.0		30	4699	891106	252
V8A	45.5	47.0		42	4700	891106	253
V9A	1.5	3.0		21	4633	891106	030
V9A	4.5	6.0		20	4634	891106	031
V9A	4.5	6.0	F	32	4635	891106	032
V9A	7.5	9.0		28	4636	891106	033
V9A	10.5	12.0		38	4637	891106	034
V9A	13.5	15.0		28	4638	891106	035
V9A	18.5	20.0		26	4639	891106	036
V9A	23.5	25.0		95	4640	891106	037
V9A	28.5	30.0		40	4641	891106	038
V9A	33.5	35.0		33	4642	891106	039
V9A	38.5	40.0		37	4643	891106	040
V10A	7.5	9.0		31	4669	891107	047
V10A	10.5	12.0		31	4671	891107	049
V10A	10.5	12.0	F	<20	4672	891107	050
V10A	13.5	15.0		39	4673	891107	051
V10A	18.5	20.0		36	4674	891107	052
V10A	18.5	20.0	F	25	4675	891107	053
V10A	23.5	25.0		37	4676	891107	054
V10A	28.5	30.0		32	4677	891107	055
V10A	33.5	35.0		37	4678	891107	056
V10A	37.5	39.0		100	4679	891107	057
V11A	1.5	3.0		98	4645	891107	058
V11A	2.0	3.0	JMC	26	4611	891102	265
V11A	4.0	5.0	JMC	20	4612	891102	266
V11A	4.5	6.0		30	4646	891107	059
V11A	7.5	9.0		24	4647	891107	060
V11A	10.5	12.0		<20	4648	891107	061
V11A	13.5	15.0		33	4649	891107	062
V11A	28.5	30.0		32	4650	891107	063
V11A	33.5	35.0		<20	4651	891107	064
V11A	35.0	36.5		90	4652	891107	065
V11B	7.5	9.0		26	4625	891106	022

TABLE G-1. POST-VENTING HYDROCARBON ANALYSES:  
BORINGS FROM VERTICAL VENT AREA  
(CONCLUDED)

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type*	(mg/kg)	Samp No.	Date	No.
V11B	10.5	12.0		25	4626	891106	023
V11B	13.5	15.0		36	4627	891106	024
V11B	18.5	20.0		36	4628	891106	025
V11B	23.5	25.0		37	4629	891106	026
V11B	28.5	30.0		30	4630	891106	027
V11B	33.5	35.0		67	4631	891106	028
V11B	37.5	39.0		55	4632	891106	029
V14A	33.5	35.0		40	4719	891107	316
V14A	38.5	40.0		33	4720	891107	317
V15A	7.5	9.0		70	4716	891107	313
V15A	10.5	12.0		62	4717	891107	314
V15A	13.5	15.0		44	4718	891107	315
E	4.5	6.0		28	4617	891102	271
E	7.5	9.0		31	4618	891102	272
E	10.5	12.0		25	4619	891102	273
E	13.5	15.0		31	4620	891102	274
E	13.5	15.0	F	25	4621	891102	275
E	18.5	20.0		100	4622	891102	276
E	23.5	25.0		182	4623	891102	277
E	28.5	30.0		75	4624	891102	278
			TB	41	4644	891106	041
			TB	43	4670	891107	048
*F=Field blank; JMC=collected with a hand auger; TB=trip blank.							

TABLE G-2. POST-VENTING HYDROCARBON ANALYSES: PILE

Borehole	Depth BLS (ft)		Samp.	Total HC	GJ	ACD Samp No.	
No.	Top	Btm	Type*	(mg/kg)	Samp No.	Date	No.
P1A	6.6	7.6		24	4603	891013	109
P2A	1	2		30	4591	891013	102
P2A	3.2	4.2		31	4602	891013	108
P2A	4.2	5.2		32	4604	891013	110
P2A	6.2	7.2		97	4606	891013	112
P3A	3.3	4.3		39	4605	891013	111
P3A	4.7	5.7		71	4607	891013	113
P4A	3.1	4.1		25	4601	891013	107
P5A	1	2		32	4590	891013	101
P5A	3.4	4.4		45	4592	891013	103
P5A	4.5	5.5		172	4600	891013	106
P6A	3	4		26	4588	891013	099
P6A	4.6	5.6		35	4589	891013	100
			TB	28	4594	891013	104
			TB	26	4595	891013	105
*TB=Trip blank							

TABLE G-3. MOISTURE CONTENT OF POST-VENTING SAMPLES

Gr. Junct.	Borehole	Depth BLS (ft)		Water Content
Samp. No.	No.	Top	Bottom	(% Dry Wt)*
4588	P6A	3	4	3.68
4589	P6A	4	5	4.04
4590	P5A	1	2	7.15
4591	P2A	1	2	6.34
4592	P5A	3	4	7.90
4594	TB			0.34
4595	TB			0.29
4600	P5A	4.5	5.5	8.83
4601	P4A	3.1	4.1	7.35
4602	P2A	3.2	4.2	5.92
4603	P1A	6.6	7.6	2.41
4604	P2A	4.2	5.2	7.18
4605	P3A	3.3	4.3	7.45
4606	P2A	6.2	7.2	7.61
4607	P3A	4.7	5.7	7.89
4609	V4	2	3	6.72
4610	V4	4	5	19.55
4611	V11B	2	3	7.66
4612	V11B	4	5	5.93
4613	V4	7.5	9	5.15
4614	V4	10.5	12	4.70
4615	V4	10.5	12	3.84
4616	V4	13.5	15	3.68
4617	E	4.5	6	2.92
4618	E	7.5	9	5.64
4619	E	10.5	12	3.52
4620	E	13.5	15	3.61
4621	E	13.5	15	2.74
4622	E	18.5	20	4.89
4623	E	23.5	25	5.32
4624	E	28.5	30	3.92
4625	V11B	7.5	9	4.43
4626	V11B	10.5	12	4.03
4627	V11B	13.5	15	3.51
4628	V11B	18.5	20	5.08
4629	V11B	23.5	25	5.06
4630	V11B	28.5	30	6.43
4631	V11B	33.5	35	4.41
4632	V11B	37.5	39	23.27
4633	V9	1.5	3	6.13
4634	V9	4.5	6	5.10
4635	V9	4.5	6	5.26
4636	V9	7.5	9	5.63
4637	V9	10.5	12	3.96
4638	V9	13.5	15	4.78

TABLE G-3. MOISTURE CONTENT OF POST-VENTING SAMPLES  
(CONTINUED)

Gr. Junct.	Borehole	Depth BLS (ft)		Water Content
Samp. No.	No.	Top	Bottom	(% Dry Wt)*
4639	V9	18.5	20	5.50
4640	V9	23.5	25	25.63
4641	V9	28.5	30	5.37
4642	V9	33.5	35	6.75
4643	V9	38.5	40	15.32
4644	TB			0.24
4645	V11	1.5	3	6.88
4646	V11	4.5	6	4.41
4647	V11	7.5	9	9.45
4648	V11	10.5	12	29.07
4649	V11	13.5	15	4.53
4650	V11	28.5	30	4.68
4651	V11	33.5	35	26.52
4652	V11	35	36.5	29.89
4653	V4	18.5	20	3.59
4654	V4B	1.5	3	6.92
4655	V4B	4.5	6	4.62
4656	V4B	7.5	9	6.11
4657	V4B	10.5	12	3.59
4658	V4B	13.5	15	4.06
4659	V4B	13.5	15	4.47
4660	V4B	17	18.5	6.71
4661	V4B	18.5	20	5.50
4662	V3	18.5	20	5.10
4663	V3	23.5	25	5.78
4664	V3	28.5	30	6.62
4665	V3	33.5	35	7.77
4666	V3	33.5	35	6.84
4667	V3	37	38.5	11.39
4668	V3	38.5	40	4.51
4669	V10	7.5	9	3.61
4670	TB			0.26
4671	V10	10.5	12	4.48
4672	V10	10.5	12	28.49
4673	V10	13.5	15	4.41
4674	V10	18.5	20	4.93
4675	V10	18.5	20	4.79
4676	V10	23.5	25	5.54
4677	V10	28.5	30	4.89
4678	V10	33.5	35	4.55
4679	V10	37.5	39	27.06
4680	V2	1.5	3	3.15
4681	V2	4.5	6	12.01
4682	V2	7.5	9	4.23
4683	V2	10.5	12	4.06

TABLE G-3. MOISTURE CONTENT OF POST-VENTING SAMPLES  
(CONCLUDED)

Gr. Junct.	Borehole	Depth BLS (ft)		Water Content
Samp. No.	No.	Top	Bottom	(% Dry Wt)*
4684	V2	10.5	12	4.48
4685	V2	13.5	15	3.94
4686	V2	18.5	20	8.36
4687	V2	23.5	25	5.64
4688	V2	38.5	40	5.67
4689	V2	43.5	45	4.75
4690	V6	48.5	50	18.98
4691	V6	53.5	55	3.84
4692	V8	1.5	3	3.49
4693	V8	4.5	6	7.54
4694	V8	23.5	25	3.43
4695	V8	26	27.5	3.35
4696	V8	28.5	30	4.73
4697	V8	33.5	35	6.99
4698	V8	38.5	40	3.05
4699	V8	43.5	45	4.77
4700	V8	45.5	47	5.79
4701	V7	1.5	3	5.30
4702	V7	4.5	6	5.33
4703	V7	7.5	9	3.96
4704	V7	10.5	12	4.38
4705	V7	10.5	12	4.60
4706	V7	13.5	15	3.75
4707	V4C	1.5	3	4.86
4708	V4C	4.5	6	4.10
4709	V4C	7.5	9	3.75
4710	V4C	10.5	12	4.68
4711	V4C	13.5	15	7.93
4712	V4C	16.5	18	4.17
4713	V4C	18.5	20	4.10
4714	V4C	28.5	30	5.93
4715	V4C	33.5	35	9.36
4716	V15	7.5	9	4.60
4717	V15	10.5	12	4.75
4718	V15	13.5	15	6.97
4719	V14	33.5	35	3.48
4720	V14	38.5	40	N/D
*(Wet Wt - Dry Wt)/Dry Wt x 100%				



TABLE G-4. POST-VENTING SAMPLES ANALYZED FOR BENZENE, TOLUENE, AND XYLENES (BTX)

GJ No.	Vent No.	Depth Interval (ft)	Total HC (mg/kg)	Total BTX (mg/kg)
4639	V9A*	18.5-20	26	<10
4664	V3A	28.5-30	300	<10
4667	V3A	37-38.5	39	<10
4673	V10A*	13.5-15	39	<10
4679	V10A*	37.5-39	100	<10
4686	V2A	18.5-20	424	<10
4687	V2A*	23.5-25	67	<10
4690	V6A*	18.5-20	35	<10
4700	V8A*	45.5-47	42	<10
4712	V4C	16.5-18	220	<10

\*Selected due to correspondence with high pre-venting total hydrocarbon content and pre-venting total BTX concentration greater than 300 mg/kg.

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING

Borehole No.	Samp Dpth BLS (ft)		Water Content (%)	PRE-VENTING SAMPLES			Water Content (%)	POST-VENTING SAMPLES			Depth Interval (ft) (3)
	Top	Bottom		Measured	Nominal	Dry wt (2)		Measured	Nominal	Dry wt (2)	
V1	1.5	3	2.43	<20	10	10				10.4	3
V1	4.5	6	4.25	<20	10	10				10	3
V1	7.5	9	4.32	<20	10	10				10	3
V1	10.5	12	5.47	<20	10	11				11	3
V1	13.5	15	4.92	<20	10	11				11	3
V1	18.5	20	N/D	<20	10	10				10	5
V1	23.5	25	N/D	<20	10	10				10	5
V1	28.5	30	N/D	<20	10	10				10	5
V1	33.5	35	N/D	<20	10	10				10	5
V1	38.5	40	N/D	<20	10	10				10	5
V1	43.5	45	N/D	<20	10	10				10	5
V1	48.5	50	14.81	<20	10	12				12	5
V2	1.5	3	2.81	<20	10	10	3.15	37	37	38	3
V2	4.5	6	5.67	320	320	339	12.01	66	66	75	3
V2	7.5	9	5.71	1400	1400	1485	4.23	32	32	33	3
V2	12.5	12	4.43	1800	1800	1884	4.27	30	30	31	3
V2	13.5	15	5.16	2300	2300	2425	3.94	32	32	33	3
V2	18.5	20	4.35	600	600	627	8.36	424	424	463	5
V2	23.5	25	7.51	5700	2085	3119	5.64	67	67	71	5
V2	28.5	30	3.63	<20	10	10				10	5
V2	33.5	35	6.35	90	90	96				96	5
V2	38.5	40	N/D	<20	10	10	5.67	33	33	35	5
V2	43.5	45	N/D	<20	10	10	4.75	37	37	39	5
V2	45	45.5	N/D	<20	10	10				10	5
V2	48.5	50	25.53	<20	10	13				13	0.5
V3	1.5	3	6.87	<20	10	11				11	4.5
V3	4.5	6	5.14	<20	10	11				11	3
V3	7.5	9	5.82	<20	10	11				11	3
V3	10.5	12	3.82	<20	10	10				10	3
V3	13.5	15	6.73	<20	10	11				10	3
V3	18.5	20	N/D	<20	10	10				10	3
V3	23.5	25	4.44	<20	10	10	5.10	53	53	56	5
V3	28.5	30	4.61	780	780	810	5.78	115	115	122	5
V3	33.5	35	5.87	825	825	865	6.62	300	300	321	5
V3	37.5	38	6.56	770	770	801	7.31	112	112	121	5
V3				4200	4200	4495	11.39	223	223	252	0.5

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS (ft)		Water Content (%)		PRE-VENTING SAMPLES			POST-VENTING SAMPLES			Depth Interval (ft) (3)	
					Measured	Nominal	Dry wt (2)	Measured	Nominal	Dry wt (2)		
V3	38.5	40	3.64	640	640	640	664	34	34	36	4.5	
V3	43.5	45	N/D	<20	<20	10	10		10	10	5	
V3	48.5	50	24.17	<20	<20	10	13		10	13	5	
V4	1.5	3	6.56	1400	1400	1400	1498	71	71	76	3	
V4	4.5	6	5.10	660	660	660	695	<20	10	12	3	
V4	7.5	9	3.89	910	910	910	947	31	31	33	3	
V4	10.5	12	4.17	1400	1400	1400	1461	24	24	25	3	
V4	13.5	15	5.31	580	840	840	887	23	23	24	3	
V4	17.5	18	5.24	2900	2900	2900	3060		29	31	0.5	
V4	18.5	20	4.87	2000	1785	1785	1876	35	35	36	4.5	
V4	23.5	25	7.73	<20	<20	10	11			11	5	
V4	28.5	30	3.27	<20	<20	10	10			10	5	
V4	33.5	35	26.22	<20	<20	10	14			14	3	
V4	38.5	40	26.78	<20	<20	10	14			14	5	
V4	43.5	45	23.27	<20	<20	10	13			13	5	
V5	1.5	3	2.75	<20	<20	10	10			10	3	
V5	4.5	6	4.09	<20	<20	10	10			10	3	
V5	7.5	9	3.29	<20	<20	10	10			10	3	
V5	10.5	12	6.41	<20	<20	10	11			11	3	
V5	12.8	13	N/D	<20	<20	10	10			10	0.2	
V5	13.5	15	4.44	<20	<20	10	10			10	2.8	
V5	18.5	20	N/D	<20	<20	10	10			10	5	
V5	23.5	25	N/D	<20	<20	10	10			10	5	
V5	28.5	30	N/D	<20	<20	10	10			10	5	
V5	33.5	35	5.64	<20	<20	10	11			11	5	
V5	38.5	40	N/D	<20	<20	10	10			10	5	
V5	43.5	45	4.65	<20	<20	10	10			10	5	
V5	48.5	50	4.78	<20	<20	10	11			11	5	
V6	1.5	3	2.46	<20	<20	10	10			10	3	
V6	4.5	6	4.97	<20	<20	10	11			11	3	
V6	7.5	9	4.04	<20	<20	10	10			10	3	
V6	10.5	12	5.96	<20	<20	10	11			11	3	
V6	13.5	15	6.65	<20	<20	10	11			11	3	
V6	18.5	20	4.89	<20	<20	10	11			11	5	
V6	23.5	25	5.41	<20	<20	10	11			11	5	

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS (ft)		Water Content (%)	PRE-VENTING SAMPLES			Water Content (%)	POST-VENTING SAMPLES			Depth Interval (ft) (3)
	Top	Bottom		Measured	JP-4 Conc (mg/kg) Nominal (1)	Dry wt (2)		Measured	JP-4 Conc (mg/kg) Nominal (1)	Dry wt (2)	
V6	28.5	30	4.47	<20	10	10				10	5
V6	33.5	35	6.62	<20	10	11				11	5
V6	38.5	40	3.73	<20	10	10				10	5
V6	43.5	45	4.19	4000	4000	4175	18.98	80	80	99	5
V6	48.5	50	3.11	2700	2850	2942	3.84	42	42	44	5
V7	1	2.5	3.93	<100	50	52	5.30	31	31	33	5
V7	5	6.5	1.47	200	200	203	5.33	34	34	36	5
V7	10	11.5	0.02	903	900	900	4.49	30	30	31	5
V7	15	16.5	0.08	<100	50	50	3.75	36	36	37	5
V7	20	21.5	0.07	<100	50	50				50	5
V7	25	26.5	0.14	<100	50	50				50	5
V7	30	31.5	1.85	<100	50	51				51	5
V7	35	36.5	0.01	<100	50	50				50	5
V7	40	41.5	0.56	<100	50	50				50	5
V7	45	46.5	0.03	<100	50	50				50	5
V7	50	51.5	0.19	<100	50	50				50	5
V8	15	3	5.84	360	380	404	3.49	24	24	25	3
V8	4.5	6	6.12	35	35	37	7.54	37	37	40	3
V8	7.5	9	5.45	<20	10	11				11	3
V8	10.5	12	6.14	<20	10	11				11	3
V8	13.5	15	17.13	<20	10	12				12	3
V8	18.5	20	N/D	<20	10	10				10	5
V8	23.5	25	2.18	<20	10	10				10	5
V8	27	27.5	N/D	680	680	680	3.43	<20	10	10	5
V8	28.5	30	N/D	<20	10	10	3.35	25	25	26	0.5
V8	33.5	35	N/D	<20	10	10	4.73	62	62	65	4.5
V8	38.5	40	3.47	560	560	580	6.99	35	35	38	5
V8	43.5	45	2.97	<20	10	10	3.05	71	71	73	5
V8	46.5	47	N/D	5900	5900	5900	4.77	30	30	32	5
V8	48.5	50	N/D	<20	10	10	5.79	42	42	45	0.5
V9	1.5	3	11.61	2900	2900	3281	6.13	21	21	22	4.5
V9	4.5	6	6.86	2000	2150	2308	5.18	26	26	27	3
V9	7.5	9	4.72	390	390	409	5.65	28	28	30	3
V9	10.5	12	7.21	360	360	388	3.96	38	38	40	3
V9	13.5	15	3.36	<20	10	10	4.78	28	28	29	3

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth		BLS (ft)	Water Content (%)		PHE-VENTING SAMPLES			POST-VENTING SAMPLES			Depth Interval (ft) (3)
	Top	Bottom		Measured	Nominal	Measured	Nominal	Dry wt (mg/kg) (2)	Measured	Nominal	Dry wt (mg/kg) (2)	
V9	18.5	20	2	5300	5800	6217	5.50	26	26	26	28	5
V9	23.5	25	2	<20	10	11	25.63	95	95	95	128	5
V9	28.5	30	3	2800	2800	2908	5.37	40	40	40	42	5
V9	33.5	35	3	850	850	907	6.75	33	33	33	35	5
V9	38.5	40	4	210	210	226	15.32	37	37	37	44	5
V9	43.5	45	4	<20	10	14					14	5
V9	48.5	50	5	<20	10	12					12	5
V10	7.5	9	9	1000	1065	1113	3.61	31	31	31	32	9
V10	10.5	12	12	2400	2400	2740	16.49	20	20	20	24	3
V10	13.5	15	15	20400	6000	8983	4.41	39	39	39	41	3
V10	18.5	20	20	2400	2400	2591	4.86	30	30	30	32	5
V10	23.5	25	25	2400	2400	2572	5.54	37	37	37	39	5
V10	28.5	30	30	<20	10	11	4.89	32	32	32	34	5
V10	33.5	35	35	<20	10	10	4.55	37	37	37	39	5
V10	38.5	39	39	6300	6350	6350	27.06	100	100	100	137	0.5
V10	39	40	40	40	40	57					57	4.5
V10	43.5	45	45	40	40	54					54	5
V10	48.5	50	50	<20	10	13					13	5
V11	1.5	3	3	1900	1900	2050	8.88	98	98	98	105	3
V11	4.5	6	6	<20	10	11	4.41	30	30	30	31	3
V11	7.5	9	9	<20	10	10	9.45	24	24	24	27	3
V11	10.5	12	12	307	307	420	29.07	<20	<20	10	14	3
V11	13.5	15	15	<20	10	11					11	3
V11	18.5	20	20	<20	10	11					11	5
V11	23.5	25	25	<20	10	10					10	5
V11	28.5	30	30	<20	10	11	4.68	32	32	32	34	5
V11	35.5	36	36	10200	10200	10200	29.89	90	90	90	128	0.5
V11	38.5	40	40	<20	10	10					10	4.5
V11	43.5	45	45	<20	10	10					10	5
V12	1.5	3	3	<20	10	10					10	5
V12	4.5	6	6	<20	10	10					10	3
V12	7.5	9	9	<20	10	11					11	3
V12	10.5	12	12	<20	10	11					11	3
V12	13.5	15	15	<20	10	11					11	3
V12	18.5	20	20	<20	10	10					10	3

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS (ft)		Water Content (%)		PRE-VENTING SAMPLES			POST-VENTING SAMPLES			Depth Interval (ft) (3)
					Measured	Nominal	Dry wt (2)	Measured	Nominal	Dry wt (2)	
V12	23.5	25	N/D		<20	10	10				5
V12	28.5	30	N/D		<20	10	10				5
V12	33.5	35	N/D		<20	10	10				5
V12	38.5	40	N/D		<20	10	10				5
V12	43.5	45	N/D		<20	10	10				5
V12	47	47.5	N/D		<20	10	10				0.5
V12	49.5	50	N/D		<20	10	10				4.5
V13	1.5	3	4.49		<20	10	10				3
V13	4.5	6	4.80		<20	10	11				3
V13	7.5	9	4.48		<20	10	10				3
V13	10.5	12	5.85		<20	10	11				3
V13	12.5	13	5.29		<20	10	11				0.5
V13	13.5	15	10.39		<20	10	11				2.5
V13	18.5	20	N/D		<20	10	10				5
V13	23.5	25	N/D		<20	10	10				5
V13	27	27.5	N/D		<20	10	10				0.5
V13	28.5	30	N/D		<20	10	10				4.5
V13	32	32.5	N/D		<20	10	10				0.5
V13	33.5	34	N/D		<20	10	10				4
V13	33.5	35	N/D		<20	10	10				1.5
V13	38.5	40	N/D		<20	10	10				5
V13	43.5	45	N/D		<20	10	10				5
V14	1.5	3	6.41		<20	10	11				5
V14	4.5	6	4.78		<20	10	11				3
V14	7.5	9	3.71		<20	10	10				3
V14	10.5	12	4.78		<20	10	11				3
V14	13.5	15	5.15		<20	10	11				3
V14	18.5	20	N/D		<20	10	10				5
V14	23.5	25	N/D		<20	10	10				5
V14	28.5	30	N/D		<20	10	10				5
V14	33.5	35	N/D		<20	10	10				5
V14	38.5	40	10.56		<20	400	447	40	40	41	5
V14	43.5	45	N/D		<20	10	10	33	33	33	5
V14	48.5	50	N/D		<20	10	10				5
V15	7.5	9	5.68		<20	10	11	70	70	73	9

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS (ft)		Water Content (%)	PRE-VENTING SAMPLES			Water Content (%)	POST-VENTING SAMPLES			Depth Interval (ft) (3)
				JP-4 Conc (mg/kg)				JP-4 Conc (mg/kg)			
	Top	Bottom		Measured	Nominal	Dry wt		Measured	Nominal	Dry wt	
V15	10	10.5	5.83								0.5
V15	10.5	12	10.78	45	45	48				48	2.5
V15	13.5	15	6.33	900	755	846	4.75	62	65		3
V15	18.5	20	5.78	<20	10	11	6.97	44	47		5
V15	23.5	25	N/D	<20	10	10				11	5
V15	28.5	30	N/D	(<20)	10	10				10	5
V15	32	32.5	N/D	<20	10	10				10	5
V15	33.5	35	23.46	<20	10	13				10	0.5
V15	37.5	38	N/D	<20	10	10				13	4.5
V15	38.5	40	N/D	<20	10	10				10	5
V15	43.5	45	N/D	(<20)	10	10				10	5
V15	48.5	50	N/D	(<20)	10	10				10	5
E	1.5	3	8.77	40	40	44				10	5
E	4.5	6	5.91	770	770	818	2.92	28	44		3
E	7.5	9	4.98	1100	1100	1158	5.64	31	29		3
E	10.5	12	12.31	1500	1500	1711	3.52	25	33		3
E	13.5	15	4.58	1600	2300	2410	3.17	28	26		3
E	18.5	20	7.95	1500	1700	1847	4.89	100	29		3
E	23.5	25	5.60	2300	2300	2437	5.32	182	105		5
E	28.5	30	4.10	1800	1800	1877	3.92	75	192		5
E	33.5	35	5.14	<20	10	11			78		5
E	38.5	40	30.81	<20	10	14			11		5
E	43.5	45	25.90	<20	10	13			14		5
E	48.5	50	23.12	<20	10	13			13		5
E	53.5	55	28.95	<20	10	14			13		5
E	57.2	57.5	N/D	<20	10	10			14		5
E	58.5	60	25.74	<20	10	13			10		0.3
E	62	62.2	N/D	<20	10	10			13		4.7
Y	1.5	3	4.46	<20	10	10			10		0.2
Y	4.5	6	4.57	<20	10	10			10		3
Y	7.5	9	4.51	<20	10	10			10		3
Y	10.5	12	3.71	<20	10	10			10		3
Y	13.5	15	5.41	<20	10	11			11		3
Y	18.5	20	N/D	<20	10	10			10		5
Y	23.5	25	3.98	<20	10	10			10		5

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS (ft)		Water Content (%)	PRE-VENTING SAMPLES			Water Content (%)	POST-VENTING SAMPLES			Depth Interval (ft) (3)
	Top	Bottom		Measured	Nominal	Dry wt (2)		Measured	Nominal	Dry wt (2)	
Y	28.5	30	4.37	<20	10	10				10	5
Y	33.5	35	24.50	<20	10	13				13	5
Y	38.5	40	N/D	(<20)	10	10				10	5
Y	43.5	45	N/D	(<20)	10	10				10	5
Y	48.5	50	4.32	<20	10	10				10	5
Y	53.5	55	3.64	<20	10	10				10	5
Y	58.5	60	23.00	<20	10	13				13	5
Y	61	61.5	N/D		10	10				10	0.5
Y	63.5	65	N/D	(<20)	10	10				10	4.5
TOTALS:											

(1) Means of field replicates, means of lab replicates, one half of detection limit  
(2) Nominal fuel conc x (1 (water content/100))  
(3) Sampled soil considered as representative of volume ABOVE sample and including sample, minus any biased samples collected in interval.  
(4) Area extends 20 ft beyond perimeter borings, boundaries midway between borings in interior of grid  
(5) (3) x (4)  
(6) (5) x 28.32 L/m<sup>3</sup>  
(7) (6) x 1.67 [the mean dry weight soil density (g/cm<sup>3</sup>) of all samples from borings #31 (V7) and #41]  
(8) (2) x (7) 1,000,000  
Blank entries indicate that analysis was not performed  
\*\*Post-venting hydrocarbon conc assumed to be equal to pre-venting conc  
Determined from screening analysis



TABLE G-5. JP 4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth Top	Samp Dpth Bottom	BLS (ft)	Soil Area (ft <sup>2</sup> )	Soil Volume (ft <sup>3</sup> )	Soil Mass (kg)	PRE-VENT SAMPLES Initial Fuel Mass (kg)	PRE-VENT SAMPLES Fuel Mass per Boring Area (kg)	POST-VENT SAMPLES Final Fuel Mass (kg)	POST-VENT SAMPLES Fuel Mass per Boring Area (kg)	JP-4 REMOVAL EFFICIENCY (%)
V1	1.5	3	1588	4764	134913	225305	2.31		2.31		
V1	4.5	6	1588	4764	134913	225305	2.35		2.35		
V1	7.5	9	1588	4764	134913	225305	2.35		2.35		
V1	10.5	12	1588	4764	134913	225305	2.38		2.38		
V1	13.5	15	1588	4764	134913	225305	2.37		2.37		
V1	16.5	20	1588	7940	224855	375508	3.76		3.76		
V1	23.5	25	1588	7940	224855	375508	3.76		3.76		
V1	28.5	30	1588	7940	224855	375508	3.76		3.76		
V1	33.5	35	1588	7940	224855	375508	3.76		3.76		
V1	38.5	40	1588	7940	224855	375508	3.76		3.76		
V1	43.5	45	1588	7940	224855	375508	3.76		3.76		
V1	48.5	50	1588	7940	224855	375508	4.41	58.71	4.41	38.71	0.00
V2	1.5	3	1481	4443	125829	210135	2.16		8.03		
V2	4.5	6	1481	4443	125829	210135	71.28		15.76		
V2	7.5	9	1481	4443	125829	210135	311.99		7.02		
V2	10.5	12	1481	4443	125829	210135	395.79		6.59		
V2	13.5	15	1481	4443	125829	210135	509.56		7.00		
V2	16.5	20	1481	7405	209715	350224	215.69		162.04		
V2	23.5	25	1481	7405	209715	350224	1032.48		24.87		
V2	28.5	30	1481	7405	209715	350224	3.63		3.50		
V2	33.5	35	1481	7405	209715	350224	33.86		12.96		
V2	38.5	40	1481	7405	209715	350224	3.50		12.25		
V2	43.5	45	1481	7405	209715	350224	3.50		13.60		
V2	45	45.5	1481	741	20972	35022	0.35		0.35		
V2	48.5	50	1481	6665	186744	315202	4.23	2651.83	4.23	278.20	89.51
V3	1.5	3	1376	4128	116919	195254	2.10		2.10		
V3	4.5	6	1376	4128	116919	195254	2.06		2.06		
V3	7.5	9	1376	4128	116919	195254	2.07		2.07		
V3	10.5	12	1376	4128	116919	195254	2.03		2.03		
V3	13.5	15	1376	4128	116919	195254	2.09		2.09		
V3	16.5	20	1376	6881	194864	325423	3.25		16.17		
V3	23.5	25	1376	6881	194864	325423	265.62		39.72		
V3	28.5	30	1376	6881	194864	325423	201.45		104.55		
V3	33.5	35	1376	6881	194864	325423	260.66		39.32		
V3	37.5	38	1376	688	19486	32542	146.28		8.19		

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS (ft)		Soil Area (ft <sup>2</sup> )	Soil Volume (L)		Soil Mass (kg)	PRE-VENT SAMPLES		POST-VENT SAMPLES		JP-4 REMOVAL EFFICIENCY (%)
	Top	Bottom		(ft <sup>2</sup> )	(L)		Initial Fuel Mass (kg)	Fuel Mass per Boring Area (kg)	Final Fuel Mass (kg)	Final Mass per Boring Area (kg)	
V3	38.5	40	1376	6193	175378	232881	194.53		10.43		
V3	43.5	45	1376	6881	194864	325423	3.25		3.25		
V3	48.5	50	1376	6881	194864	325423	4.29	1169.69	4.23	238.22	79.63
V4	1.5	3	1485	4455	126161	210688	315.67		16.04		
V4	4.5	6	1485	4455	126161	210688	146.53		2.62		
V4	7.5	9	1485	4455	126161	210688	199.48		6.69		
V4	10.5	12	1485	4455	126161	210688	307.79		5.28		
V4	13.5	15	1485	4455	126161	210688	186.90		5.03		
V4	17.5	18	1485	742	21027	35115	107.46		1.07		
V4	18.5	20	1485	6682	189241	316032	593.00		11.47		
V4	23.5	25	1485	7425	210268	351147	3.81		3.81		
V4	28.5	30	1485	7425	210268	351147	3.63		3.63		
V4	33.5	35	1485	7425	210268	351147	4.76		4.76		
V4	38.5	40	1485	7425	210268	351147	4.76		4.76		
V4	43.5	45	1485	7425	210268	351147	4.58	1878.37	4.58	65.94	56.28
V5	1.5	3	1180	3540	100260	167434	1.72		1.72		
V5	4.5	6	1180	3540	100260	167434	1.75		1.75		
V5	7.5	9	1180	3540	100260	167434	1.73		1.73		
V5	10.5	12	1180	3540	100260	167434	1.79		1.79		
V5	12.8	13	1180	236	6884	11162	0.11		0.11		
V5	13.5	15	1180	3304	93376	156271	1.64		1.64		
V5	18.5	20	1180	5900	167099	279056	2.79		2.79		
V5	23.5	25	1180	5900	167099	279056	2.79		2.79		
V5	28.5	30	1180	5900	167099	279056	2.79		2.79		
V5	33.5	35	1180	5900	167099	279056	2.96		2.96		
V5	38.5	40	1180	5900	167099	279056	2.79		2.79		
V5	43.5	45	1180	5900	167099	279056	2.93		2.93		
V5	48.5	50	1180	5900	167099	279056	2.93	28.71	2.93	28.71	0.00
V6	1.5	3	588	1764	49962	83436	0.86		0.86		
V6	4.5	6	588	1764	49962	83436	0.88		0.88		
V6	7.5	9	588	1764	49962	83436	0.87		0.87		
V6	10.5	12	588	1764	49962	83436	0.89		0.89		
V6	13.5	15	588	1764	49962	83436	0.89		0.89		
V6	18.5	20	588	2940	83269	139060	1.46		1.46		
V6	23.5	25	588	2940	83269	139060	1.47		1.47		

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Sample Depth BLS (ft)		Soil Area (ft <sup>2</sup> )	Soil Volume (ft <sup>3</sup> )	Soil Mass (kg)	PRE-VENT SAMPLES		POST-VENT SAMPLES		JP-4 REMOVAL EFFICIENCY (%)
	Top	Bottom				Initial Fuel Mass (kg) (8)	Fuel Mass per Boring Area (kg)	Final Fuel Mass (kg) (8)	Final Mass per Boring Area (kg)	
V6	28.5	30	588	2940	139060	1.46		1.46		
V6	33.5	35	588	2940	139060	1.49		1.49		
V6	38.5	40	588	2940	139060	1.44		1.44		
V6	43.5	45	588	2940	139060	580.59		13.73		
V6	48.5	50	588	2940	139060	409.06	1001.35	6.07	31.51	96.85
V7	1	2.5	744	3722	105418	9.16		5.76		
V7	5	6.5	744	3722	105418	35.74		6.32		
V7	10	11.5	744	3722	105418	158.41		5.53		
V7	15	16.5	744	3722	105418	8.81		6.58		
V7	20	21.5	744	3722	105418	8.81		8.80		
V7	25	26.5	744	3722	105418	8.81		8.80		
V7	30	31.5	744	3722	105418	8.97		8.98		
V7	35	36.5	744	3722	105418	8.80		8.80		
V7	40	41.5	744	3722	105418	8.85		8.80		
V7	45	46.5	744	3722	105418	8.81		8.80		
V7	50	51.5	744	3722	105418	8.82	273.99	8.80	85.99	68.61
V8	1.5	3	697	2091	98887	39.91		2.46		
V8	4.5	6	697	2091	98887	3.69		3.96		
V8	7.5	9	697	2091	98887	1.05		1.09		
V8	10.5	12	697	2091	98887	1.05		1.09		
V8	13.5	15	697	2091	98887	1.19		1.19		
V8	18.5	20	697	3485	98690	1.65		1.65		
V8	23.5	25	697	3485	98690	1.68		1.71		
V8	27	27.5	697	348	9869	11.21		0.43		
V8	28.5	30	697	3136	88821	1.48		9.65		
V8	31.5	35	697	3465	98690	1.65		6.20		
V8	38.5	40	697	3485	98690	95.61		12.07		
V8	43.5	45	697	3485	98690	1.70		5.19		
V8	46.5	47	697	348	9869	97.24		0.73		
V8	48.5	50	697	3136	88821	1.48	260.59	1.48	48.89	81.24
V9	1.5	3	737	2210	62578	342.86		2.34		
V9	4.5	6	737	2210	62578	241.23		2.87		
V9	7.5	9	737	2210	62578	42.78		3.10		
V9	10.5	12	737	2210	62578	40.55		4.14		
V9	13.5	15	737	2210	62578	1.08		3.07		

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Opth		BLS (ft)	Soil Area (ft <sup>2</sup> )	Soil Volume (ft <sup>3</sup> )	Soil Mass (kg)	PRE-VENT SAMPLES		POST-VENT SAMPLES		JP-4 REMOVAL EFFICIENCY (%)
	Top	Bottom					Initial Fuel Mass (kg)	Fuel Mass per Boring Area (kg)	Final Fuel Mass (kg)	Final Mass per Boring Area (kg)	
V9	18.5	20	737	3683	104297	174176	1082.87		4.79		
V9	23.5	25	737	3683	104297	174176	1.85		22.25		
V9	28.5	30	737	3683	104297	174176	506.47		7.36		
V9	33.5	35	737	3683	104297	174176	157.92		6.16		
V9	38.5	40	737	3683	104297	174176	39.33		7.61		
V9	43.5	45	737	3683	104297	174176	2.38		2.44		
V9	48.5	50	737	3683	104297	174176	2.12	2461.44	2.09	68.22	97.23
V10	7.5	9	600	5399	152913	255364	284.29		8.21		
V10	10.5	12	500	1800	50971	85121	233.20		2.04		
V10	13.5	15	600	1800	50971	85121	764.64		3.47		
V10	18.5	20	600	3000	84952	141869	367.57		4.47		
V10	23.5	25	600	3000	84952	141869	364.82		5.56		
V10	28.5	30	600	3000	84952	141869	1.52		4.77		
V10	33.5	35	600	3000	84952	141869	1.49		5.50		
V10	38.5	39	500	300	8495	14187	90.09		1.95		
V10	39	40	600	2700	76456	127682	7.29		7.28		
V10	43.5	45	600	3000	84952	141869	7.72		7.66		
V10	48.5	50	600	3000	84952	141869	1.86	2124.48	1.81	52.76	97.52
V11	1.5	3	1188	3564	100932	168557	345.48		17.74		
V11	4.5	6	1188	3564	100932	168557	1.78		5.39		
V11	7.5	9	1188	3564	100932	168557	1.76		4.47		
V11	10.5	12	1188	3564	100932	168557	70.78		2.38		
V11	13.5	15	1188	3564	100932	168557	1.77		1.95		
V11	18.5	20	1188	5940	168221	280929	2.96		3.09		
V11	23.5	25	1188	5940	168221	280929	2.81		2.81		
V11	28.5	30	1188	5940	168221	280929	2.95		9.43		
V11	35.5	36	1188	594	16822	28093	286.55		3.61		
V11	38.5	40	1188	5346	151399	252836	2.53		2.53		
V11	43.5	45	1188	5940	168221	280929	2.81	722.18	2.81	56.00	92.25
V12	1.5	3	1499	4497	127357	212686	2.18		2.18		
V12	4.5	6	1499	4497	127357	212686	2.23		2.23		
V12	7.5	9	1499	4497	127357	212686	2.24		2.24		
V12	10.5	12	1499	4497	127357	212686	2.27		2.27		
V12	13.5	15	1499	4437	127357	212686	2.25		2.25		
V12	18.5	20	1499	7495	212261	354476	3.54		3.54		

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS (ft)		Soil Area (ft <sup>2</sup> )	(ft <sup>3</sup> )	Soil Volume (L)	Soil Mass (kg)	PRE-VENT SAMPLES		POST-VENT SAMPLES		JP-4 REMOVAL EFFICIENCY (%)
	Top	Bottom					Initial Fuel Mass (kg)	Fuel Mass per Boring Area (kg)	Final Fuel Mass (kg)	Final Mass per Boring Area (kg)	
V12	23.5	25	1499	7495	212261	354476	3.54		3.54		
V12	28.5	30	1499	7495	212261	354476	3.54		3.54		
V12	33.5	35	1499	7495	212261	354476	3.54		3.54		
V12	38.5	40	1499	7495	212261	354476	3.54		3.54		
V12	43.5	45	1499	7495	212261	354476	3.54		3.54		
V12	47	47.5	1499	750	212261	354476	0.35		0.35		
V12	48.5	50	1499	6746	191035	319029	3.19	35.99	3.19	35.99	0.00
V13	1.5	3	1409	4227	119705	199908	2.09		2.09		
V13	4.5	6	1409	4227	119705	199908	2.10		2.10		
V13	7.5	9	1409	4227	119705	199908	2.09		2.09		
V13	10.5	12	1409	4227	119705	199908	2.12		2.12		
V13	12.5	13	1409	704	19951	33318	0.33		0.33		
V13	13.5	15	1409	3522	99754	166590	1.86		1.86		
V13	18.5	20	1409	7045	199509	333180	3.33		3.33		
V13	23.5	25	1409	7045	199509	333180	3.33		3.33		
V13	27	27.5	1409	704	19951	33318	0.33		0.33		
V13	28.5	30	1409	6340	179558	299862	3.00		3.00		
V13	32	32.5	1409	704	19951	33318	0.33		0.33		
V13	33.5	34	1409	5636	159607	266544	2.67		2.67		
V13	33.5	35	1409	2113	59853	99954	1.00		1.00		
V13	38.5	40	1409	7045	199509	333180	3.33		3.33		
V13	43.5	45	1409	7045	199509	333180	3.33	31.28	3.33	31.28	0.00
V14	1.5	3	1512	4536	128460	214527	2.29		2.29		
V14	4.5	6	1512	4536	128460	214527	2.25		2.25		
V14	7.5	9	1512	4536	128460	214527	2.23		2.23		
V14	10.5	12	1512	4536	128460	214527	2.25		2.25		
V14	13.5	15	1512	4536	128460	214527	2.26		2.26		
V14	18.5	20	1512	7560	214099	357546	3.58		3.58		
V14	23.5	25	1512	7560	214099	357546	3.58		3.58		
V14	28.5	30	1512	7560	214099	357546	3.58		3.58		
V14	33.5	35	1512	7560	214099	357546	3.58		3.58		
V14	38.5	40	1512	7560	214099	357546	159.80		14.82		
V14	43.5	45	1512	7560	214099	357546	3.58		3.58		
V14	48.5	50	1512	7560	214099	357546	3.58	192.64	3.58	55.78	71.04
V15	7.5	9	1608	14472	409347	684445	7.26		50.22		

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Opth 8LS (ft)		Soil Area (ft <sup>2</sup> )	Soil Volume (ft <sup>3</sup> )		Soil Mass (kg)	PRE-VENT SAMPLES		POST-VENT SAMPLES		JP-4 REMOVAL EFFICIENCY (%)
	Top	Bottom		(ft <sup>3</sup> )	(L)		Initial Fuel Mass (kg)	Fuel Mass per Boring Area (kg)	Final Fuel Mass (kg)	Final Mass per Boring Area (kg)	
V15	10	10.5	1608	804	22769	38025	1.82		1.63		
V15	10.5	12	1608	4020	113846	190123	160.85		12.38		
V15	13.5	15	1608	4824	136616	228148	2.44		10.79		
V15	18.5	20	1608	8040	227693	380247	4.04		4.04		
V15	23.5	25	1608	8040	227693	380247	3.80		3.00		
V15	28.5	30	1608	8040	227693	380247	3.80		3.80		
V15	32	32.5	1608	804	22769	38025	0.38		0.38		
V15	33.5	35	1608	7236	204924	342222	4.47		4.47		
V15	37.5	38	1608	8040	227693	380247	3.80		3.80		
V15	38.5	40	1608	8040	227693	380247	3.80		3.80		
V15	43.5	45	1608	8040	227693	380247	3.80		3.80		
V15	48.5	50	1608	8040	227693	380247	3.80	204.06	3.80	106.92	47.61
E	1.5	3	368	1105	31289	52253	2.29		2.29		
E	4.5	6	368	1105	31289	52253	2.76		2.29		
E	7.5	9	368	1105	31289	52253	60.49		1.72		
E	10.5	12	368	1105	31289	52253	89.38		1.35		
E	13.5	15	368	1105	31289	52253	125.95		1.51		
E	18.5	20	368	1441	52148	87088	100.82		8.16		
E	23.5	25	368	1441	52148	87088	212.19		16.74		
E	28.5	30	368	1441	52148	87088	193.47		6.80		
E	33.5	35	368	1441	52148	87088	0.92		0.92		
E	38.5	40	368	1441	52148	87088	1.26		1.26		
E	43.5	45	368	1441	52148	87088	1.18		1.18		
E	48.5	50	368	1441	52148	87088	1.13		1.13		
E	53.5	55	368	1441	52148	87088	1.23		1.23		
E	57.2	57.5	368	110	3129	5225	0.05		0.05		
E	58.5	60	368	1731	49020	81853	1.10		1.10		
E	62	62.2	368	74	2086	3484	0.03	864.27	0.03	47.97	94.45
Y	1.5	3	392	1176	33308	55624	0.58		0.58		
Y	4.5	6	392	1176	33308	55624	0.58		0.58		
Y	7.5	9	392	1176	33308	55624	0.58		0.58		
Y	10.5	12	392	1176	33308	55624	0.58		0.58		
Y	13.5	15	392	1176	33308	55624	0.59		0.59		
Y	18.5	20	392	1960	55513	92706	0.93		0.93		
Y	23.5	25	392	1960	55513	92706	0.97		0.97		

TABLE G-5. JP-4 MASS BALANCE: VERTICAL VENT FIELD, PRE- AND POST-VENTING  
(CONCLUDED)

Borehole No.	Sample Depth		BLS (ft)	Soil Area (ft <sup>2</sup> )	Soil Volume (ft <sup>3</sup> )		Soil Mass (kg)	PRE-VENT SAMPLES		POST-VENT SAMPLES		JP-4 REMOVAL EFFICIENCY (%)
	Top	Bottom			(113)	(1)		Initial Fuel Mass per Boring (kg) (8)	Fuel Mass per Boring Area (kg) (8)	Final Fuel Mass per Boring Area (kg) (8)		
Y	28.5	30	30	392	1960	55513	92706	0.97		0.97		
Y	33.5	35	35	392	1960	55513	92706	1.23		1.23		
Y	38.5	40	40	392	1960	55513	92706	0.93		0.93		
Y	43.5	45	45	392	1960	55513	92706	0.93		0.93		
Y	48.5	50	50	392	1960	55513	92706	0.97		0.97		
Y	53.5	55	55	392	1960	55513	92706	0.96		0.96		
Y	58.5	60	60	392	1960	55513	92706	1.20		1.20		
Y	61	61.5	61.5	392	1960	55513	9271	0.09		0.09		
Y	63.5	65	65	392	1764	49962	83436	0.83	12.92	0.83	0.00	
TOTALS:				224704	919083	26028428	43467475	13952.50		1288.01	90.77	
				(1) Means of field replicates; means of lab replicates; one-half of detection limit.								
				(2) = Nominal fuel conc x (1 - (water content/100))								
				(3) Sampled soil considered as representative of volume ABOVE & including sample, minus biased samples in interval								
				(4) Area extends 20 ft beyond perimeter borings; boundaries midway between borings in interior of grid								
				(5) = (3) x (4)								
				(6) = (5) x 28.32 L/ft <sup>3</sup>								
				(7) = (6) x 1.67 (the mean dry weight soil density (g/cm <sup>3</sup> ) of all samples from borings #31 (V7) and #41)								
				(8) = (2) x (7) / 1,000,000								
				Blank entries indicate that analysis was not performed.								
				**Post-venting hydrocarbon conc. assumed to be equal to pre-venting conc.								
				†Determined from screening analysis								

TABLE G-6. JP-4 MASS BALANCE: EXCAVATED SOIL PILE, PRE- AND POST-VENTING

Borehole No.	Samp Dpth BLS(ft)		PRE-VENTING SAMPLES			POST-VENTING SAMPLES		
			Water Content (%)		JP-4 Conc (mg/kg)	Water Content (%)		JP-4 Conc (mg/kg)
	Top	Bottom	Measured	Nominal		Measured	Nominal	
P1	1.0	2.0	<10	5	(1)			(2)
P1	3.2	4.2	<10	5				5.5
P1	6.4	7.4	1400	1400				5
P2	1.0	2.0	180	180	1508	2.41	24	25
P2	3.2	4.2	230	230	193	6.34	30	32
P2	4.2	5.2	920	920	247	5.92	31	33
P2	6.2	7.2	1000	1000	987	7.18	32	34
P3	1.0	2.0	45	45	1089	7.61	97	104
P3	3.0	4.0	1400	1400	49			49
P3	4.5	5.5	3250	3250	1499	7.45	39	42
P4	1.0	2.0	5.90	4.0	3494	7.89	71	76
P4	3.0	4.0	780	780	42			42
P4	6.5	7.5	70	70	852	7.35	25	27
P5	1.0	2.0	1160	1160	75			70
P5	3.3	4.3	2100	2100	1247	7.15	32	34
P5	4.3	5.3	740	740	2237	7.90	45	49
P6	1.0	2.0	40	40	76	8.83	172	187
P6	3.0	4.0	40	40	43			70
P6	4.6	5.6	470	470	507			43
P7	1.0	2.0	3450	3450	3693	26	26	26
P7	3.2	4.2	<10	5		35	35	35
P7	6.8	7.8	352	352	5			5
P8	1.0	2.0	596	596	10			10
P8	3.0	4.0	7.66	7.66	32			32
P8	4.0	5.0	6.44	6.44	11			11
P8	5.3	6.3	6.78	6.78	40			40
P9	1.0	2.0	5.57	5.57	43			43
P9	3.3	4.3	4.47	4.47	69			69
P9	4.5	5.5	35	35	5			5
P10	1.0	2.0	6.86	6.86	37			37
P10	3.0	4.0	2.89	2.89	43			43
P10	6.6	7.6	3.18	3.18	5			5
P11	1.0	2.0	5.06	5.06	10			10
P11	3.0	4.0	2.85	2.85	11			11
P11	5.1	6.1	3.64	3.64	10			10
P11			5.29	5.29	11			11



TABLE G-6. JP-4 MASS BALANCE: EXCAVATED SOIL PILE, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS(ft)		Water Content (%)	PRE-VENTING SAMPLES			Water Content (%)	POST-VENTING SAMPLES		
	Top	Bottom		Measured	Nominal	Dry wt (2)		Measured	Nominal	Dry wt (2)
P12	1.0	2.0	5.79	10	10	11				11
P12	3.2	4.2	6.23	50	50	53				53
P12	4.6	5.6	6.63	45	45	48				48
(1) Means of field reof lab replicates; one-half of detection limit										
(2) = Nominal fuel conc x (1-(water content/100))										
(3) = Cell Length x Width x Depth										
(4) = (3) x 28.32 L/ft3										
(5) = (4) x 1.67 ft soil density (g/cm3) of all samples from borings #31 (V7) and #41										
(6) = (2) x (5)/1,000,000										
*Blank entries indicate that analysis was not performed.										
**Post-venting hydrocarbon limit to be equal to pre-venting conc.										

TABLE G-6. JP-4 MASS BALANCE: EXCAVATED SOIL PILE, PRE- AND POST-VENTING  
(CONTINUED)

Borehole No.	Samp Dpth BLS(ft)		Cell Dimensions (ft)		Soil Volume		Soil Mass (kg) (5)	Initial Fuel		Final Fuel	
	Top	Bottom	Depth	Length	Width	(ft3) (3)		Mass (kg) (6)		Mass (kg) (6)	
P1	1.0	2.0	2	27.5	6	330	9346	15807	0.08		0.08
P1	3.2	4.2	2	32.5	11	715	20249	33815	0.17		0.17
P1	6.4	7.4	4	37.5	16	2400	67968	113507	171.24		2.79
P2	1.0	2.0	2	27.5	13	715	20249	33815	6.51		1.08
P2	3.2	4.2	2	32.5	13	845	23930	39984	9.88		1.31
P2	4.2	5.2	1.5	37.5	13	731	20709	34584	34.13		1.19
P2	6.2	7.2	1.5	37.5	13	731	20709	34584	38.98		3.61
P3	1.0	2.0	2	27.5	6	330	9346	15807	0.76		0.76
P3	3.0	4.0	2	32.5	11	715	20249	33815	50.69		1.42
P3	4.5	5.5	2	37.5	16	1200	33984	56753	198.30		4.34
P4	1.0	2.0	2	37.5	6	450	12744	21282	0.90		0.89
P4	3.0	4.0	2	37.5	11	825	23394	39018	33.22		1.05
P4	6.5	7.5	4	37.5	16	2400	67968	113507	8.49		7.95
P5	1.0	2.0	2	37.5	13	975	27612	46112	57.52		1.59
P5	3.3	4.3	2	37.5	13	975	27612	46112	103.17		2.24
P5	4.3	5.3	1.5	37.5	13	731	20709	34584	27.20		6.48
P6	1.0	2.0	2	37.5	13	731	20709	34584	2.58		2.42
P6	3.0	4.0	2	37.5	6	450	12744	21282	0.91		0.92
P6	3.0	4.0	2	37.5	11	825	23394	39018	19.79		1.01
P6	4.0	5.0	2	37.5	16	1200	33984	56753	208.99		1.99
P7	1.0	2.0	2	37.5	6	450	12744	21282	0.11		0.11
P7	3.2	4.2	2	37.5	11	825	23394	39018	0.40		0.40
P7	6.8	7.8	4	37.5	16	2400	67968	113507	3.61		3.61
P8	1.0	2.0	2	37.5	13	975	27612	46112	0.50		0.50
P8	3.0	4.0	2	37.5	13	975	27612	46112	1.87		1.87
P8	4.0	5.0	1.5	37.5	13	731	20709	34584	1.48		1.48
P8	5.3	6.3	1.5	37.5	13	731	20709	34584	2.37		2.37
P9	1.0	2.0	2	37.5	6	450	12744	21282	0.11		0.11
P9	3.3	4.3	2	37.5	11	825	23394	39018	1.45		1.45
P9	4.5	5.5	2	37.5	16	1200	33984	56753	2.43		2.43
P10	1.0	2.0	2	37.5	6	330	9346	15807	0.08		0.08
P10	3.0	4.0	2	32.5	11	715	20249	33815	0.35		0.35
P10	6.8	7.8	4	37.5	16	2400	67968	113507	1.19		1.19
P11	1.0	2.0	2	27.5	13	715	20249	33815	0.35		0.35
P11	3.0	4.0	2	32.5	13	845	23930	39984	0.41		0.41
P11	5.1	6.1	3	37.5	13	1463	41418	69168	0.73		0.73



TABLE G-7. RESULTS OF ANALYSIS FOR PETROLEUM DISTILLATE CONSTITUENTS  
IN GROUNDWATER FROM MONITORING WELL RST-1, OCTOBER 1989

COMPOUND	CONCENTRATION ( $\mu\text{g/L}$ )
Benzene	<5
Toluene	<5
Ethylbenzene	<5
Xylene (total)	<5
Naphthalene	<10
2-Methylnaphthalene	<10
Acenaphthylene	<10
Acenaphthene	<10
Fluorene	<10
Phenanthrene	<10
Anthracene	<10
Fluoranthene	<10
Pyrene	<10
Benz(a)anthracene	<10
Chrysene	<10
Benzo(b)fluoranthene	<10
Benzo(k)fluoranthene	<10
Benzo(a)pyrene	<10
Indeno(1,2,3-cd)pyrene	<10
Dibenz(a,h)anthracene	<10
Benzo(g,h,i)perylene	<10

## APPENDIX H

### TABLE OF CONTENTS OF APPENDICES J AND K (UNPUBLISHED)

Copies of the unpublished Appendices J and K are available from the authors at ORNL or the Chemical/Physical Treatment Technology Area Manager, HQ AFESC/RDVW, Tyndall AFB, Florida.

TABLE H-1. TABLES OF CONTENTS OF UNPUBLISHED APPENDICES J AND K  
(UNPUBLISHED APPENDICES AVAILABLE FROM ORNL OR AFESC)

CONTENTS OF APPENDIX J

1. Geological Boring Logs
2. Soil Sample Analytical Reports
3. Gas Sample Analytical Reports
4. Calculation of Hydrocarbon Removal by Volatilization
5. Appendices to Battelle Report, "Enhanced Biodegradation through Soil Venting,"  
by R. E. Hinchee, D. C. Downey, R. R. Dupont, and M. Arthur
  - a. Comparison of Oxygen and Carbon Dioxide Measurement Techniques
  - b. Mass Balance Worksheet for Hydrocarbon Removal by Volatilization and Biodegradation
  - c. Results of In Situ Respiration Tests
6. Methods
  - a. Hydrocarbon Analyses
  - b. Neutron Tube Installation, Logging Procedure, and Calibration
7. QA/QC Reports
  - a. Gas Analysis by GC
  - b. THA Calibration

CONTENTS OF APPENDIX K

1. *In Situ* Permeability Tests
  - a. Transient Recovery Procedures
  - b. Steady-State Procedure
  - c. Summary of *In Situ* Permeability Tests
2. Flow Model Simulation
  - a. Calibration to Pilot Test
  - b. Flow in Multiple Vent Configurations
  - c. Comparison of Flow Models to Flow Tests
3. Description of Flow Models
  - a. Analytic Model
  - b. FEMAIR User's Manual
  - c. Listing of AIRGRD3D.FOR